Review Article

Nanotechnology in Precision Agriculture Applications of Nanosensors in Soil, Crop and Water Management

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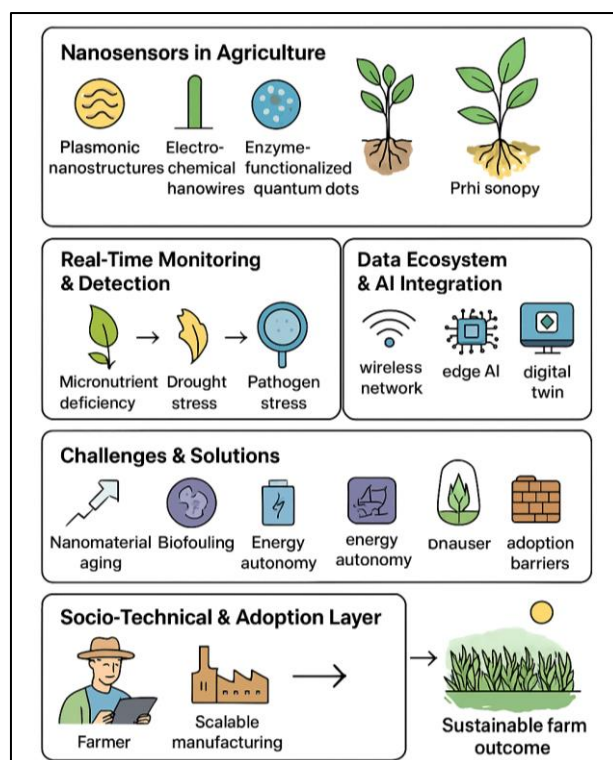[8]Department of Agriculture, MNS University of Agriculture Multan, Pakistan

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Abstract

Graphical Abstract

The convergence of nanotechnology and precision agriculture is redefining the future of sustainable food systems. As global agricultural systems face mounting pressures from climate volatility, resource depletion, and population growth, nanosensors engineered at the molecular scale offer a revolutionary toolkit for real-time, high-resolution monitoring of soil nutrients, crop physiological status, and water dynamics. Despite burgeoning research, a critical synthesis of how these nanoscale devices functionally integrate across the agro-ecosystem from rhizosphere to canopy, from lab to field remains

absent. This review fills that void by providing a transdisciplinary analysis of nanosensor platforms, deployment architectures, and data ecosystems tailored for precision agriculture. We evaluate cutting-edge materials including plasmonic nanostructures, electrochemical nanowires, enzyme-functionalized quantum dots, and molecularly imprinted polymers for their sensitivity, environmental stability, and field-deployable form factors. Novel insights are presented on overlooked challenges: nanomaterial aging under UV/soil pH, biofouling interference, energy autonomy for remote sensing, and regulatory fragmentation across jurisdictions. Beyond technology, we examine socio-technical adoption barriers and propose scalable manufacturing and farmer-engagement models. This review does not merely catalog innovations it constructs a unified framework for evaluating "agricultural nanosensor readiness," identifying critical gaps and accelerators for real-world impact. By bridging materials science, agronomy, data engineering, and policy, we chart a course toward intelligent, self-regulating farms where nanosensors serve as the nervous system of sustainable agriculture transforming data into decisions, and innovation into resilience.

Keywords: Nanotechnology; Precision Agriculture; Nanosensors; Soil Health Monitoring; Smart Irrigation; Crop Phenotyping; Sustainable Agri-Tech.

INTRODUCTION

The global agricultural enterprise confronts an existential paradox, it must simultaneously expand output to nourish a burgeoning population and contract its environmental footprint to preserve planetary boundaries (Fang *et al.,* 2015). Conventional, input-intensive farming characterized by blanket fertilizer application, scheduled irrigation, and reactive pest control is increasingly unsustainable (Shaaban *et al.,* 2024). It squanders finite resources, exacerbates greenhouse gas emissions, and degrades soil and water systems. In response, precision agriculture has emerged as the dominant paradigm for the 21st century, a philosophy grounded in spatially and temporally explicit management, where every drop of water, granule of fertilizer, and square meter of soil is optimized through data-driven insight (Wen *et al.,* 2025). Yet, the efficacy of precision agriculture is intrinsically tethered to the quality, density, and timeliness of its sensory inputs. Herein lies the bottleneck: traditional sensing technologies, whether satellite imagery, drone-based multispectral cameras, or in-field electrochemical probes, often lack the resolution, specificity, or durability required to capture the dynamic, microscale processes governing plant health and soil vitality (Gano *et al.,* 2024).

Nanotechnology, particularly through the advent of nanosensors, offers a disruptive solution. Engineered at dimensions comparable to biomolecules, nanosensors exploit quantum mechanical and surface phenomena to detect analytes with extraordinary sensitivity, often at parts-per-billion levels, and with molecular specificity (Darwish *et al.,* 2024). More critically, their diminutive size permits non-invasive integration into biological matrices: embedded within root tissues to monitor ion fluxes, laminated onto leaf surfaces to track transpiration and pathogen ingress, or dispersed in irrigation lines to map nutrient distribution in real time. Unlike bulky, power-hungry conventional sensors, many nanosensors operate passively, require minimal calibration, and can be manufactured at scale using low-cost techniques such as inkjet printing or colloidal self-assembly (Kulkarni *et al.,* 2022). Recent breakthroughs have yielded nanosensors capable of detecting nitrogen stress before chlorosis manifests, identifying fungal infection at the spore germination stage, and quantifying soil moisture gradients at centimeter-scale resolution, feats unattainable with legacy technologies. Despite these advances, the field remains fragmented. Research is siloed, materials scientists develop novel nanostructures without agronomic context; agronomists test prototypes without understanding signal drift or interference; data scientists build models without access to high-fidelity, continuous field data (Kim *et al.,* 2025). Moreover, few reviews adopt a systems perspective evaluating how nanosensors function not in isolation, but as interconnected nodes within the soil-plant-water-atmosphere continuum. Critical questions remain unanswered: How do nanosensors perform under diurnal temperature swings or prolonged soil moisture?

This review transcends disciplinary boundaries to deliver a unified, application-driven synthesis of nanosensors in precision agriculture (DELEANU *et al.,* 2025). Our scope spans three core domains: soil (nutrient cycling, pH, microbial activity), crop (physiological stress, disease, growth kinetics), and water (irrigation efficiency, contaminant detection, salinity). We do not merely describe technologies; we interrogate their readiness for field deployment. We analyze material innovations for environmental resilience, evaluate deployment strategies for spatial-temporal coverage, dissect data integration pipelines for decision support, and confront ecological and regulatory uncertainties. Crucially, we introduce the concept of "Agricultural Nanosensor Readiness Levels" (ANRL), a staged framework analogous to Technology Readiness Levels, to benchmark progress from lab validation to farm-scale implementation. Our contributions are manifold. First, we establish a functional taxonomy of agricultural nanosensors based on transduction mechanism (optical, electrochemical, mechanical), target analyte (nutrient, hormone, pathogen, pollutant), and operational matrix (soil solution, xylem sap, leaf apoplast). Second, we identify performance benchmarks, detection limits, response times, and operational lifespans, that define field viability. Third, we expose critical gaps in scalability, energy autonomy, and farmer accessibility. Fourth, we propose policy levers and innovation

ecosystems to accelerate adoption. By synthesizing disparate advances into a coherent, forward-looking framework, this review empowers researchers to design context-aware nanosensors, enables agronomists to interpret nanoscale data within macro-scale management, and equips policymakers to govern this emerging frontier responsibly. The goal is unambiguous: to transform nanosensors from laboratory marvels into the foundational infrastructure of a resilient, intelligent, and equitable agricultural future, where every plant speaks, every soil particle is known, and every drop of water is accounted for.

Material Architectures for Agronomic Sensing: Beyond Conventional Nanoparticles

The evolution of nanosensor technology for precision agriculture demands a radical departure from conventional nanoparticle platforms, such as bare metallic or metal oxide nanostructures, which, despite their initial promise, often falter under the complex, dynamic, and biologically rich conditions of real-world agro-ecosystems (Yadav *et al.,* 2023). Soil matrices teeming with organic acids, humic substances, and microbial exudates; plant apoplastic fluids laden with polyphenols, proteins, and fluctuating ionic gradients; and irrigation waters subject to pH shifts, salinity spikes, and suspended colloids, all conspire to degrade sensor performance through fouling, signal drift, and non-specific binding. To overcome these limitations, next-generation material architectures are being engineered not merely for sensitivity, but for *contextual intelligence*: materials that actively adapt to their environment, resist degradation, self-repair damage, and maintain analyte specificity amidst biological noise (Phogat *et al.,* 2025). Biohybrid nanosensors, fusing synthetic nanomaterials with biological recognition elements such as aptamers, enzymes, or engineered peptides, offer unparalleled selectivity by leveraging the evolutionary precision of biomolecular interactions. For instance, quantum dots functionalized with nitrate-specific aptamers can distinguish NO_3^- from structurally similar anions like Cl^- or SO_4^{2-} in soil pore water, while enzyme-mimetic nanozymes embedded in mesoporous silica enable continuous, interference-free detection of reactive oxygen species (ROS) in drought-stressed leaves (Mugwanya *et al.,* 2023). Complementing these are stimuli-responsive hydrogels and polymer matrices, engineered to swell, shrink, or change conformation in response to target analytes or environmental triggers (pH, temperature, redox potential), which act as molecular gates, enhancing signal-to-noise ratios by physically excluding interferents or amplifying transduction only upon specific binding events. Recent innovations include glucose-responsive hydrogels that modulate fluorescence intensity in tandem with root-zone sugar exudation, and pH-switchable nanogels that activate only under pathogen-induced apoplastic acidification (Delaunois *et al.,* 2014). Perhaps most transformative are self-healing nanocomposite matrices, incorporating dynamic covalent bonds, reversible supramolecular interactions, or microcapsule-based repair agents, that autonomously restore structural and functional integrity after mechanical abrasion, UV degradation, or biofilm colonization. These materials not only extend operational lifespan from days to seasons but also reduce recalibration burdens and maintenance costs, critical for scalable deployment. Furthermore, surface engineering strategies such as zwitterionic coatings, biomimetic lipid bilayers, and antifouling polymer brushes are being integrated to minimize non-specific adsorption of proteins and polysaccharides, a persistent challenge in plant and soil sensing (Asha *et al.,* 2021). Together, these advanced material architectures represent a paradigm shift: from passive, static sensors to active, adaptive, and ecologically integrated diagnostic interfaces. Their development requires deep collaboration across synthetic biology, soft matter physics, and agronomic science, not only to optimize performance under controlled conditions, but to ensure resilience, specificity, and sustainability in the messy, magnificent complexity of living agricultural systems (Altieri *et al.,* 2015).
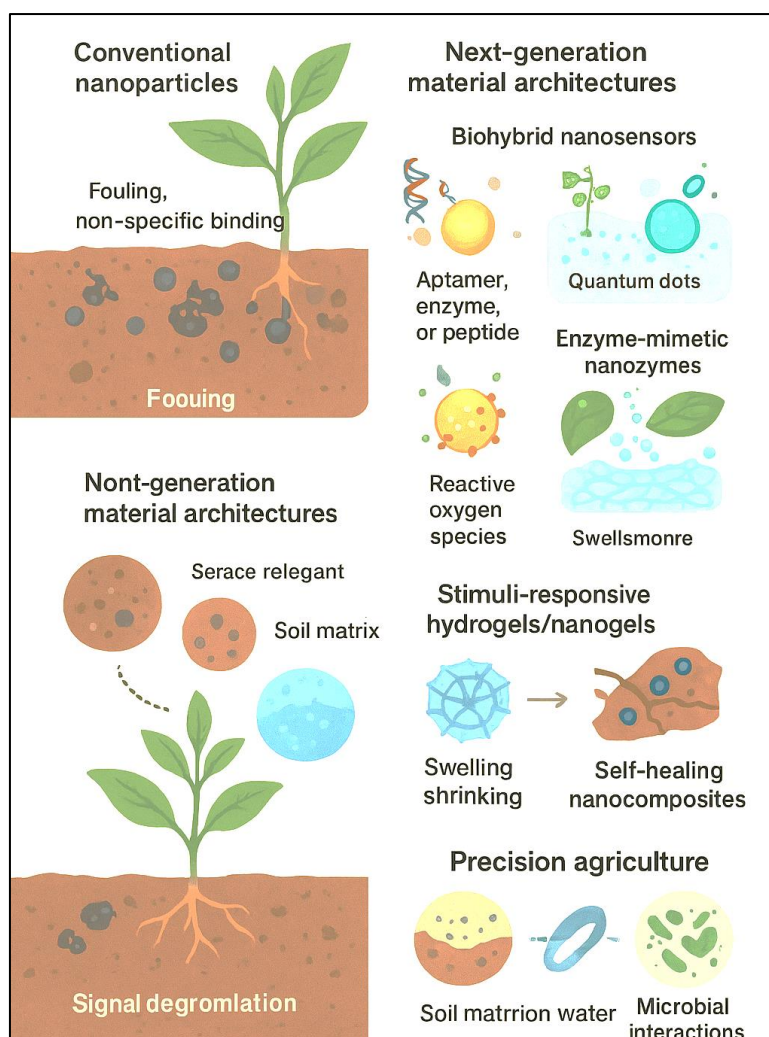
Fig 1: Material Architectures for Agronomic Sensing: Beyond Conventional Nanoparticles

In Situ Intelligence: Embedding Nanosensors in the Plant-Soil-Water Continuum

The concept of *in situ* intelligence in precision agriculture hinges on the strategic embedding of nanosensors directly within the dynamic interfaces of the plant-soil-water continuum transforming passive landscapes into responsive, data-generating ecosystems (Liu *et al.,* 2019). Unlike ex situ or proximal sensing technologies that infer conditions indirectly, embedded nanosensors operate at the point of biological and geochemical action, capturing real-time, high-fidelity signals from microenvironments that dictate crop performance and resource efficiency. Deployment modalities span a spectrum of architectural and functional designs, each calibrated to specific agronomic zones and analytical objectives (Singh *et al.,* 2021). Root-zone probes often composed of flexible nanowire arrays or hydrogel-encapsulated plasmonic nanoparticles are engineered for insertion into rhizospheres to monitor ion fluxes (e.g., NO_3^-, K^+, NH_4^+), pH gradients, and redox potentials with micron-scale spatial resolution. These probes offer unparalleled insight into nutrient bioavailability and root exudate dynamics but confront challenges related to mechanical fragility, biofouling by microbial biofilms, and potential disruption of root architecture during insertion, raising questions about long-term invasiveness and plant physiological interference. At the aerial interface, leaf-mounted nanosensor patches fabricated from ultrathin, breathable substrates functionalized with fluorophore-conjugated aptamers or conductive polymer matrices enable non-invasive tracking of stomatal conductance, phytohormone surges (e.g., abscisic acid under drought), and early pathogen biomarkers e.g., reactive oxygen species or pathogen-associated molecular patterns (Zheng *et al.,* 2022). While minimally invasive and capable of continuous epidermal adhesion without impairing photosynthesis, these patches face environmental degradation from UV radiation, rain abrasion, and wind shear, which can compromise signal stability and data continuity over extended growing seasons. Meanwhile, irrigation-integrated nanosensors deployed within drip lines, subsurface emitters, or fertigation manifolds function as distributed chemical sentinels, detecting real-time fluctuations in nutrient concentration, salinity, pesticide residues, and microbial contaminants as water traverses delivery systems. These systems excel in temporal resolution and scalability

across large fields but sacrifice spatial granularity, often averaging conditions over meters of flow path, and risk clogging or signal attenuation due to particulate load or biofilm accumulation within conduits (Indraratna *et al.,* 2025). Critically, the choice of deployment modality involves inherent trade-offs: root-embedded sensors maximize spatial precision at the cost of potential plant stress and limited scalability; leaf patches balance non-invasiveness with environmental vulnerability; irrigation-integrated systems prioritize coverage and automation but dilute microscale heterogeneity. Emerging hybrid architectures such as seed-coating

nanosensors that germinate with the plant or biodegradable sensor-laden mulches that dissolve post-harvest, seek to reconcile these tensions by aligning sensor lifecycle with crop phenology. Ultimately, the intelligent embedding of nanosensors within the plant-soil-water matrix is not merely a technical exercise but a reimagining of agriculture as a cyber-physical system, where data generation is seamlessly woven into the fabric of biological processes enabling not just observation, but anticipatory, closed-loop management of agricultural ecosystems with unprecedented spatial, temporal, and biochemical resolution (Silva *et al.,* 2022).

Table 1: In Situ Intelligence: Embedding Nanosensors in the Plant-Soil-Water Continuum

Nanosensor Type / Architecture	Deployment Zone / Interface	Target Analytes / Parameters	Advantages / Strengths	Challenges / Limitations
Graphene FET root-zone probe	Rhizosphere near feeder roots	Nitrate, ammonium, phosphate	High sensitivity, low noise, ion-selective gating enables real-time nutrient maps	Fouling by root exudates; calibration drift in variable ionic strength
SWCNT leaf-mounted patch (ratiometric)	Leaf epidermis/mesophyll contact	Abscisic acid (ABA), H_2O_2 (ROS)	Non-invasive phyllosphere readout; stomatal dynamics resolved in minutes	Photobleaching over long sun exposure; adhesive-induced microdamage risk
Hydrogel–ionic conductor pH microprobe	Root–soil interface	pH, carbonate alkalinity	Soft, conformal; minimal root perturbation; stable over wet–dry cycles	Hydrogel dehydration in arid spells; hysteresis at extremes
Plasmonic Au nanoislands (SERS)	Leaf surface cuticle	Pesticide residues, phytoalexins	Molecular specificity; ultra-trace detection on-field	Signal variability with leaf microtopography; need for spectral expertise
MOF-coated chemiresistor	Soil pore water in root zone	Ammonia, ethylene, volatile N species	Selective sorption; tunable MOF chemistry; compact	Waterlogging blocks pores; MOF degradation under acidic soils
Quantum-dot fluorescence moisture probe	Bulk soil / potting medium	Volumetric water content, salinity proxy	Optical readout; distributed nodes for spatial mapping	Fluorescence quenching by humics; requires optical access
DNA-aptamer/AuNP colorimetric dipstick	Irrigation lines / fertigation	Pathogen markers (e.g., Xanthomonas DNA), toxins	Rapid on-site yes/no; low-cost screening inline	Single-use; semi-quantitative; susceptible to nuclease activity
Magnetic nanoparticle flow/Cl^- sensor	Drip emitters / laterals	Flow anomalies, chloride (salinity)	Non-invasive clamp-on readout; pipeline health + water quality	Magnetic interference; requires periodic re-zeroing
Fiber Bragg grating (nano-coated)	Root crown / stem collar	Temperature, strain (turgor proxy), sap flow	Multiplexable, EMI-immune, long cable runs	Brittle if poorly encapsulated; coupling to soft tissue tricky
Microneedle nanoelectrode sap patch	Leaf petiole / stem phloem	Sugars, K^+, phytohormones	Minimal wound; true in situ sap analytics	Clogging by phloem proteins; ethical concerns in perennials
Paper-based microfluidic–nanocarbon strip	Leaf underside near stomata	Transpiration rate, pH, nitrate in guttation	Ultralight, disposable; fast mass transfer	Short operational lifetime; hydration dependence
EIS nanosensor on PEDOT:PSS mesh	Rhizoplane wrapping	Root exudates (organic acids), ion conductivity	Captures exudation rhythms; conformal 3D wrap	Biofilm overgrowth alters baselines; mesh installation delicate

Nanosensor Type / Architecture	Deployment Zone / Interface	Target Analytes / Parameters	Advantages / Strengths	Challenges / Limitations
LSPR nanocup array	Rhizosphere microzones	Phosphate speciation, Fe^{2+}/Fe^{3+}	Label-free, sub-second kinetics; surface chemistry tunable	Refractive index cross-sensitivity; soil particle abrasion
Surface acoustic wave (SAW) microchip	Leaf midrib / stem	Turgor pressure change via mass loading	Wireless interrogation possible; high temporal resolution	Sensitive to vibration/handling; packaging for outdoor use
Nanopore osmometer (solid-state)	Xylem stream (microtubed)	Sap osmotic potential, Na^+/Cl^- spikes	Mechanistic insight into salinity stress; compact	Insertion is invasive; fouling by xylem tyloses
Upconversion nanoparticle (UCNP) probe	Sub-epidermal leaf tissue	ROS ($\bullet OH$, $^1O_2$), Ca^{2+} signals	Deep optical penetration with NIR; low autofluorescence	Rare-earth leaching concerns; excitation safety protocols
Triboelectric nanogenerator (TENG) leaf sensor	Leaf blade edge	Raindrop impact, wind-induced motion (ET proxy)	Self-powered; event-based irrigation cues	Output variability with leaf age; weatherproofing needed
Nanocellulose–AgNW flexible patch	Fruit peel / canopy microclimate	Temperature, humidity, VOCs	Biodegradable substrate; conforms to curved tissues	Silver migration/tarnish; peel adhesion over maturation
MXene (Ti_3C_2Tx) microband chemiresistor	Wet soil horizon	Sulfate, nitrate via redox impedance	High conductivity; printable; responds under flooded conditions	Oxidation of MXene; requires encapsulation against O_2
Microbial fuel cell (MFC) nano-enabled anode	Rooted soil bed	Redox potential, biologically available C	Energy self-harvesting; integrates soil microbiome status	Slow response; seasonal microbial variability
rGO–polyaniline composite pH fiber	Dripline emitters	pH, EC in fertigation	Inline continuous control; retrofit friendly	Polymer aging under chlorine; hysteresis after strong acids
SERS-on-drone leaf swab (portable)	Canopy survey / multiple leaves	Pathogen-specific metabolites, pesticide drift	Rapid, spatially extensive scouting; minimal plant contact	Sample-to-sample variability; requires operator training
Biodegradable PLGA nanoresistor bead	Seed coat / rhizosphere at germination	Temperature, moisture, ABA/GA ratio (proxy)	Early-stage vigor diagnostics; degrades after use	Limited lifetime; signal strength vs. bead loading
Zeolite–CNT hybrid root probe	Root hairs zone	K^+/NH_4^+ selectivity, micronutrients	Ion sieving + electronic readout; millimeter-scale mapping	Selectivity shifts with competitive ions; zeolite clogging
Photonic crystal hydrogel dot array	Leaf surface (stomatal grid)	Vapor pressure deficit (VPD), leaf wetness	Colorimetric, camera-readable; passive grids enable high throughput	Spectral readout depends on illumination; gel fatigue

From Signal to Decision: Data Integration Architectures for Real-Time Farm Management

The transition from raw nanosensor data to actionable agronomic intelligence represents one of the most critical and underexplored frontiers in the evolution of precision agriculture (Ashique *et al.,* 2025). While advances in nanomaterials have enabled unprecedented sensitivity and spatial resolution in monitoring soil ion fluxes, plant metabolite dynamics, and irrigation water quality, the true value of these measurements is unlocked only when they are contextualized, correlated, and converted into predictive, decision-ready outputs. This necessitates a robust, multi-layered data integration architecture that operates seamlessly across the continuum from field-edge hardware to cloud-based analytics. At the foundational layer, edge-computing frameworks are indispensable for preprocessing high-frequency, heterogeneous nanosensor streams filtering noise, compensating for drift, performing local calibration, and compressing data thereby reducing latency and bandwidth constraints while preserving signal integrity (Zhang*et al.,* 2024). These edge nodes,

often embedded within sensor hubs or autonomous drones, execute lightweight machine learning models such as convolutional neural networks for spectral pattern recognition or recurrent networks for time-series anomaly detection to flag early indicators of nutrient deficiency, pathogen invasion, or water stress before visible symptoms manifest. Above this, IoT mesh networks orchestrate communication between distributed nanosensor arrays, gateway aggregators, and farm machinery, enabling decentralized, fault-tolerant data flow even in low-connectivity rural environments; protocols such as LoRaWAN, NB-IoT, and Zigbee are increasingly optimized for low-power, high-latency tolerance, ensuring continuous telemetry from root-zone probes to canopy-mounted micro-spectrometers (Marini *et al.,* 2022). Crucially, these architectures must be interoperable with digital twin platforms that simulate crop-soil-water interactions in silico, allowing real-time sensor inputs to dynamically recalibrate predictive models of yield, evapotranspiration, or fertilizer response. Advanced AI pipelines including federated learning to preserve data privacy across farms, transfer learning to adapt models from controlled environments to open fields, and explainable AI (XAI) to render algorithmic decisions interpretable to agronomists are now being deployed to transform nanosensor-derived micro-phenotypes into macro-scale management prescriptions: when to irrigate, where to apply micronutrients, which cultivars to prioritize under forecasted heat stress. The integration challenge extends beyond algorithms to semantics: ontologies and metadata standards (e.g., AgroPortal, Crop Ontology) are essential to harmonize data from disparate nanosensor modalities electrochemical, plasmonic, fluorometric into unified knowledge graphs that link molecular-scale events to field-level outcomes (Kant *et al.,* 2024). Moreover, human-in-the-loop systems, where farmer feedback continuously refines model accuracy, ensure that data-driven insights remain grounded in practical agronomy rather than abstract analytics. As nanosensors proliferate, the scalability of these architectures will determine whether precision agriculture evolves into a truly autonomous, anticipatory system one were nanoscale signals trigger macroscale interventions with surgical precision, transforming farms into self-optimizing ecosystems governed not by calendar or intuition, but by real-time, physics-informed, AI-augmented intelligence (Sahibzada *et al.,* 2025).

Table 2: From Signal to Decision: Data Integration Architectures for Real-Time Farm Management

Deployment Modality / Architecture	Target Parameters / Analytes	Material / Sensor Design	Advantages / Opportunities	Challenges / Limitations
1. Root-zone vertical nanowire array (insertable rod)	Nitrate (NO_3^-) transient fluxes at cm-scale depth	Silicon/graphene vertical nanowires functionalized with ion-selective peptides; microfluidic sampling ports	High spatial resolution of nitrate hotspots; enables pulse-fertilizer optimization and root uptake mapping	Biofouling of nanowires; mechanical fragility during insertion; calibration drift in complex ionic backgrounds
2. Hydrogel-encapsulated plasmonic rootsensor (soft conformal)	Phosphate (PO_4^{3-}) speciation and local PO_4 pulses	Stimuli-responsive polyacrylamide hydrogel embedding Au nanoshells conjugated to phosphate-binding aptamers; LSPR readout	Conformal contact with rhizosphere; optical readout tolerant to electrical noise; sensitive to micro-scale pulses	Diffusion-limited response time; interference from organic phosphates; hydrogel swelling alters optical path-length
3. Ion-selective nanofiber mat for K^+ mapping	Potassium (K^+) depletion zones around roots	Electrospun polymer nanofibers containing valinomycin-doped CNT electrodes with multiplexed microcontacts	Rapid, distributed K^+ sensing across root zone; useful for precision K fertilization	Ionophore poisoning over time; selectivity vs. NH_4^+; need for encapsulation to prevent soil abrasion
4. Redox-gradient microarray (planar)	Soil redox potential (Eh) and dissolved Fe(II)/Mn(II)	Mixed-metal oxide nanoelectrodes ($IrOx/WO_3$) patterned on flexible substrate with differential potentiometry	Maps anaerobic microsites; informs denitrification and greenhouse gas hotspots	Electrode corrosion in acidic soils; reference electrode stability; complex interpretation without O_2 co-measurement

Deployment Modality / Architecture	Target Parameters / Analytes	Material / Sensor Design	Advantages / Opportunities	Challenges / Limitations
5. Root-exudate sugar nanoprobe (chemoresistive)	Glucose, sucrose pulses from exudation	Conductive polymer nanoparticles (PEDOT:PSS) functionalized with boronic acid receptors; resistive readout	Real-time exudation dynamics linked to root phenology and microbe recruitment	Nonselective binding to other diols; matrix effects from humic substances; regeneration between pulses
6. Leaf-mounted fluorophore-conjugated aptamer patch	Abscisic acid (ABA) and H_2O_2 dynamics in stomatal guard cells	Thin, breathable polymer patch with fluorophore-quencher aptamer pair; ratiometric fluorescence imaging	Noninvasive monitoring of stomatal signaling for drought early-warning and irrigation scheduling	Photobleaching under sunlight; mechanical adhesion under rain/wind; need for portable fluorimeter for field use
7. Conductive polymer mesh for chlorophyll fluorescence	Photosynthetic electron transport efficiency (Fv/Fm proxies)	Stretchable PEDOT:PSS mesh with integrated light-emitting and photodiode pairs	High-throughput leaf stress mapping; continuous diurnal monitoring of photoinhibition	Pressure on leaf altering physiology; temperature sensitivity of polymer sensors; spectral overlap with ambient light
8. Leaf-surface VOC nanosensor array (chemiresistor)	Volatile organic compounds indicating pathogen or herbivore attack (e.g., methyl salicylate, green leaf volatiles)	Functionalized SWCNT chemiresistors in microarray; pattern recognition (machine learning) for VOC fingerprints	Early, noninvasive biotic stress detection enabling targeted interventions	Low analyte vapor pressure; cross-sensitivity to humidity/temperature; needs robust ML model trained per crop
9. Drip-line microfluidic fertigation sampler	Real-time EC, nitrate, phosphate in irrigation/emitted fertigation	Microfluidic channel with embedded ion-selective nanofilms and capacitive electrodes; optical turbidity sensor	Continuous fertigation quality control; detection of dosing errors and nutrient stratification	Particulate clogging; sensor fouling by biofilms; requires inline maintenance access
10. Fertigation-integrated organophosphate detector	Pesticide residues (organophosphates) in applied water	Molecularly imprinted polymer (MIP) nanoparticles coupled to electrochemical transducer; disposable cartridge	Immediate detection of contaminated water inputs; prevents phytotoxic dosing	MIP cross-reactivity; low ppb detection in turbid water; cartridge replacement logistics
11. Irrigation-pipe antifouling nanoprobe (electrochemical)	Microbial load and biofilm metabolic activity	Silver-doped antifouling coating with embedded enzyme-amplified nanobiosensors (e.g., lactate oxidase)	Prolonged in-line monitoring with suppressed biofouling; informs disinfection timing	Silver leaching regulatory concerns; enzyme lifetime; signal attenuation by scaling
12. Seed-coating nanosensor (single-seed telemetry)	Early seedling phytohormone (auxin, gibberellin) signatures and moisture	Biodegradable polymer microsensors (PLGA) loaded with fluorescent affinity probes and NFC energy harvester	Very early detection of germination success and stress; seed-level phenotyping in breeding	Power/data retrieval constraints; limited payload mass; ensuring coating does not affect germination
13. Biodegradable mulch embedded chemosensor	Soil salinity (Na^+/Cl^-) and moisture under mulch	Cellulose-based biodegradable film with printed ion-selective organic	Passive, single-season sensing with natural decomposition;	Short operational lifetime tied to degradation; variable

Deployment Modality / Architecture	Target Parameters / Analytes	Material / Sensor Design	Advantages / Opportunities	Challenges / Limitations
		electrochemical transistors (OECTs)	spatial mapping under mulches	signal as film degrades; manufacturing scale-up
14. Biohybrid plant–electrode interface (living conductive biofilm)	Plant electrophysiological signals and sap ion composition (K⁺, Ca²⁺)	Engineered conductive biofilm (Geobacter-like) grown at root–electrode interface with nanoscale interdigitated electrodes	Direct coupling to plant signaling; low-power continuous telemetry; deep insight into whole-plant stress propagation	Biosafety and stability of engineered microbes; regulatory hurdles; complex signal deconvolution
15. Stimuli-responsive hydrogel nanosensor (pH/redox)	Localized rhizosphere pH shifts and ROS (H_2O_2) gradients	Dual-layer hydrogel: pH-sensitive fluorophore layer + redox-responsive ferrocene nanoparticles; optical fiber readout	Simultaneous multi-parameter mapping enabling root stress mapping and microbe activity inference	Photobleaching, limited optical penetration in opaque soils; mechanical wear; need for fiber routing
16. Self-healing nanocomposite rhizoelectrode	Long-term electron transfer and microbial fuel cell monitoring	Carbon nanotube-epoxy matrix with microencapsulated healing agent (Diels–Alder chemistry) and Pt-nanoparticle catalytic nodes	Extends in-soil sensor lifetime; maintains electrical contact in shifting soils; useful for long trials	Complexity of heal activation cycles; encapsulant leakage; cost and reproducibility
17. Antifouling coated porous nanosensor for microbial contaminants	E. coli / coliform detection in irrigation return flows	Zwitterionic antifouling brush coating over porous silica nanoparticle immunosensor with electrochemical readout	Reduces false negatives from biofilms; rapid on-farm water hygiene screening	Antibody stability; low bacterial load detection limit; regeneration vs. disposable tradeoffs
18. Nanophotonic stomatal-aperture sensor (optical microsensor)	Real-time stomatal aperture dynamics via refractive index change (proxy for transpiration)	Silicon nitride ring resonator integrated in flexible substrate; local leaf micro-optics	High temporal resolution of stomatal kinetics; informs precision deficit irrigation	Coupling to leaf microtopography; need for sub-micron alignment; sensitivity to surface contaminants
19. Pesticide metabolite biosensing patch (leaf)	Specific pesticide metabolites (e.g., chlorpyrifos oxon) in phyllosphere	Enzyme-based nanosensor on porous graphene with catalytic turnover and amperometric detection	Direct evidence of on-plant pesticide degradation and exposure risk to pollinators	Enzyme inhibitors in mixed exposures; ambient temperature dependence; sensor poisoning
20. Soil enzyme-activity nanosensor (urease/ phosphatase)	Localized enzymatic activity as proxy for microbial nutrient cycling	Nanoparticle enzyme substrates that yield electroactive reporters upon cleavage; immobilized on microbeads	Functional readout of soil biological activity; links to nutrient availability beyond bulk chemistry	Heterogeneous soil contact; substrate diffusion limits; potential perturbation of local microbiome
21. Sap-interstitial nanoprobe for reactive oxygen species (ROS)	H_2O_2 and superoxide bursts in xylem/phloem during abiotic/biotic stress	Redox-sensitive nanodiamonds with surface-bound peroxidase-mimetic sites and optical lifetime modulation	Direct in-plant oxidative stress quantification; discriminates transient vs sustained ROS events	Insertion wounding response confounds signal; limited probe recycling; optical readout penetration

Deployment Modality / Architecture	Target Parameters / Analytes	Material / Sensor Design	Advantages / Opportunities	Challenges / Limitations
22. Multiplexed spectral nanocomposite for heavy metals	Spatial patterns of Cd^{2+}, Pb^{2+}, and Cu^{2+} in rhizosphere	Layered nanocomposite film with orthogonal chelators and spectrally distinct plasmonic nanocrystals	Simultaneous multi-metal mapping; informs phytoremediation and food-safety risk	Cross-chelation and competitive binding; soil particulate scattering; long-term stability in acidic soils

Ecological and Regulatory Frontiers: Lifecycle, Fate, and Governance of Agricultural Nanomaterials

The integration of nanosensors into open-field agriculture heralds a new era of precision and efficiency, yet it simultaneously introduces complex ecological and regulatory challenges that demand rigorous, preemptive scrutiny (Lo *et al.*, 2020). Unlike controlled laboratory or greenhouse environments, agricultural ecosystems are dynamic, heterogeneous, and ecologically interconnected conditions under which the environmental fate of nanomaterials becomes unpredictable and potentially consequential. A critical frontier in the responsible deployment of agricultural nanosensors lies in understanding their lifecycle: from synthesis and functionalization, through operational deployment in soil, plant, or water matrices, to eventual degradation, transformation, or accumulation. Nanomaterials whether metallic (e.g., silver, gold, quantum dots), carbon-based (e.g., graphene, nanotubes), or polymeric (e.g., molecularly imprinted hydrogels), exhibit divergent behaviors under environmental stressors such as UV radiation, pH fluctuations, enzymatic activity, and microbial colonization (Saylan *et al.*, 2024). For instance, silver nanoparticles, widely explored for their antimicrobial sensing capabilities, may oxidize to release Ag^+ ions that inhibit soil nitrifying bacteria or accumulate in root tissues, disrupting nutrient uptake. Similarly, carbon nanotubes, while prized for their mechanical robustness and conductivity, resist biodegradation and may persist in soil aggregates for years, altering porosity and microbial habitat structure. The risk of trophic transfer further complicates this landscape: nanomaterials absorbed by crops may enter the food chain, potentially bioaccumulating in herbivores or even humans, with unknown chronic toxicity profiles. Current biodegradability benchmarks often derived from industrial or biomedical contexts are ill-suited for agricultural applications, lacking standardized protocols that account for soil type, organic matter content, redox potential, or crop species variability (Ramezani *et al.*, 2023). Equally pressing is the fragmented and reactive nature of global regulatory governance. While the European Union's REACH framework and the U.S. EPA's TSCA have begun to incorporate nanomaterial-specific provisions, most agricultural nanosensors fall into regulatory gray zones classified neither as pesticides, fertilizers, nor conventional electronics, and thus escaping mandatory environmental impact assessments. Jurisdictions such as India, Brazil, and China, where nanotechnology adoption in agriculture is accelerating, often lack nano-specific regulatory infrastructure entirely, creating disparities in risk management and market access (Amutha *et al.*, 2024). Moreover, the absence of internationally harmonized definitions what constitutes a "nanosensor" versus a "nano-enabled device," or how to quantify "environmentally significant release" impedes coherent policy development. Emerging efforts by OECD and ISO to establish testing guidelines for nanomaterials in soil and water are promising but remain non-binding and insufficiently tailored to the unique exposure pathways of agricultural nanodevices. To navigate this frontier, a proactive, transdisciplinary governance model is imperative — one that couples lifecycle assessment (LCA) with ecological risk modeling, embeds "safety-by-design" principles into nanosensor engineering, and fosters regulatory agility through adaptive, science-informed policy frameworks. Only through such integrated stewardship can the promise of nanosensors in precision agriculture be realized without compromising the ecological integrity of the very systems they seek to sustain (Fathi Qarachal *et al.*, 2025).
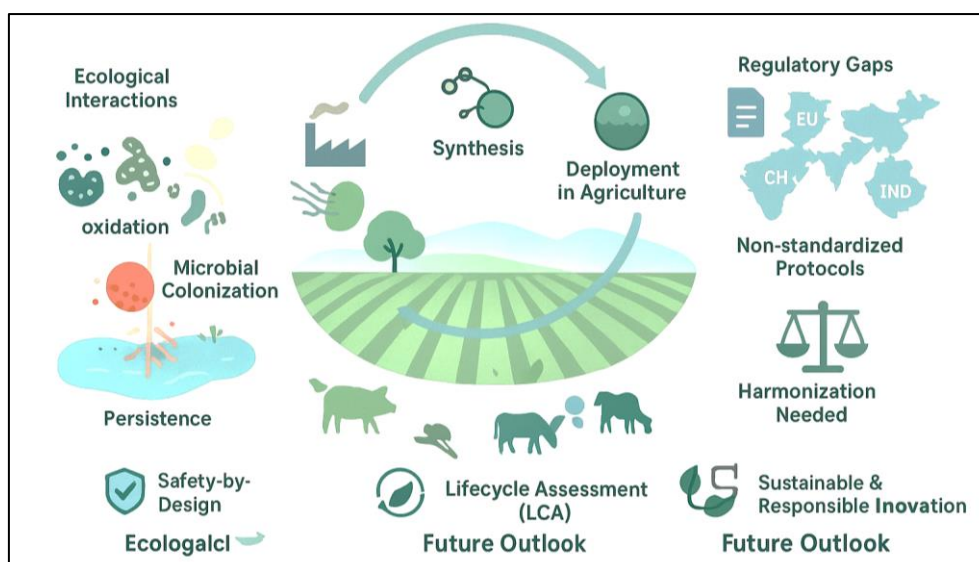
Fig. 2: Ecological and Regulatory Frontiers: Lifecycle, Fate, and Governance of Agricultural Nanomaterials

Scaling the Nano-Agro Revolution: Pathways from Lab Prototype to Global Adoption

The transition of nanosensor technologies from controlled laboratory environments to heterogeneous, resource-constrained agricultural landscapes represents one of the most formidable yet critically underexamined challenges in the evolution of precision agriculture (John *et al.,* 2023). While academic literature abounds with proof-of-concept demonstrations showcasing extraordinary sensitivity, multiplexing capabilities, and molecular specificity, the chasm between these innovations and their widespread, economically viable deployment on farms often termed the "valley of death" remains vast and inadequately bridged. Scaling the nano-agro revolution demands more than incremental improvements in material science or signal transduction; it necessitates a systemic re-engineering of the innovation pipeline to align with the economic, operational, and cultural realities of global farming communities (Agbugba *et al.,* 2024). Central to this transformation is the development of scalable manufacturing paradigms that move beyond cleanroom-based, batch-limited synthesis toward roll-to-roll printing, aerosol deposition, and bio-templated self-assembly techniques capable of producing nanosensors at meter-scale throughput and sub-cent-per-unit cost. Equally vital are cost-reduction strategies that leverage agricultural waste streams such as cellulose nanofibrils from crop residues or biochar-derived carbon nanostructures as sustainable, low-cost substrates, while adopting modular, open-source hardware architectures that minimize dependency on proprietary components. However, technological affordability alone is insufficient without farmer-centric design principles that prioritize usability, interpretability, and resilience: nanosensors must be deployable by non-specialists, require minimal maintenance under field conditions (resisting biofouling, UV degradation, mechanical abrasion), and deliver actionable insights through intuitive interfaces whether via smartphone alerts, voice-based advisories, or integration with existing farm management software (Delgado *et al.,* 2021). Crucially, adoption is not merely a technical or economic challenge but a socio-institutional one; thus, policy incentives must be strategically deployed to de-risk early-stage adoption, including subsidies for pilot deployments, tax credits for agri-tech startups, streamlined regulatory pathways for "green" nanomaterials with proven biodegradability, and public-private partnerships that co-develop solutions with farmer cooperatives rather than for them. Furthermore, capacity-building initiatives such as nanosensor literacy programs, localized repair and recalibration hubs, and data sovereignty frameworks that ensure farmers retain ownership of generated insights are essential to foster trust and long-term engagement. Only through this integrated, multi-stakeholder approach harmonizing materials innovation with manufacturing scalability, economic accessibility with user-centered design, and technological promise with institutional enablement can the nano-agro revolution transcend the confines of academic journals and demonstration plots to become a democratized, globally accessible infrastructure for sustainable intensification, empowering smallholders and industrial farms alike to navigate the converging crises of food security, climate adaptation, and ecological stewardship with unprecedented precision and resilience (Thangamani *et al.,* 2025).

CONCLUSION

Nanotechnology, particularly through advanced nanosensors, is revolutionizing precision agriculture by enabling real-time, molecular-level monitoring of soil nutrients, crop stress, and water dynamics shifting farm management from reactive to predictive and significantly enhancing sustainability, yield stability, and resource efficiency. These devices, leveraging plasmonic, electrochemical, and biofunctionalized platforms, offer

unprecedented sensitivity for early detection of deficiencies, pathogens, and irrigation needs, while integration with AI and IoT transforms data into autonomous, site-specific interventions. Yet, widespread adoption remains constrained by unresolved environmental risks, including nanomaterial fate and ecotoxicity alongside scalability barriers, high production costs, field durability limitations, and fragmented regulatory frameworks. The true novelty lies not in isolated sensor performance, but in envisioning nanosensors as adaptive, biodegradable, energy-autonomous nodes within an intelligent agro-ecosystem. Future breakthroughs must prioritize eco-design with controlled degradation, multiplexed sensing in complex biological matrices, and farmer-inclusive deployment models. Bridging this gap demands coordinated innovation in materials science, policy harmonization, and scalable manufacturing ensuring nanotechnology evolves from lab-scale promise to globally accessible infrastructure, empowering resilient, data-driven agriculture for a food-secure future.

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