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Recent Advances in Smart Polymer Composites for Plant Health Monitoring: A Strategic Integration of Sensing Mechanisms and Computational Intelligence

Arvind Rehalia[1], Kajal Kaul[2,]*, Surinder Kaur[3], Ruchi Sharma[4], Sanjeev Sanyal[5]

Abstract

Plant health assessment is crucial for agricultural production and food security, as plant diseases significantly affect crop yields and quality. This paper reviews the applications of polymers and composite materials in the evaluation of plant health, focusing on both natural and artificial polymers, carbon materials, and polymeric–nanoparticle composite materials. Various types of sensing principles, such as colorimetry, fluorimetry, surface plasmon resonance (SPR), surface enhanced Raman scattering (SERS), and interferometry, are examined, as well as optical, electrochemical, and volatile organic compounds (VOCs)-based methods combined with imaging tools. Traditional methods are also considered for comparison purposes. In addition, the research examines the approaches used to process the obtained data using polymer systems, paying particular attention to deep learning algorithms and pattern recognition, as well as image processing techniques. Some limitations, including environmental stability, selectivity, scale-up, user friendliness, and regulatory issues, are identified. Also, various Research Questions, Quality Assessment attributes, the mapping of RQs with QAs and Literature Review has been formulated to analyze the role of the approaches for Plant Health Assessment. These approaches pave the way forward for future innovation and research in this field. It is then followed by the Result and Conclusion sections, and later by the future scope.

Keywords: Polymer composites, plant health, sensing, deep learning, quality assessment

INTRODUCTION

Plant pathogens cause significant financial losses and reduced crop quality. Researchers are leveraging polymer and composite materials to develop "smart" sensing systems. Composite materials in this pursuit provide refined characteristics and more sensitivity to disease biomarkers, such as volatile organic compounds (VOCs) and pathogenic enzymes. Integration of nanocomponents enables the development of portable, field devices. This is an innovative way to utilize polymers and composites in a hybrid manner to smartly detect vulnerable plants under pathogenic attack. Strength-to-weight ratios and passive mechanical functioning were typically used in the construction of conventional composites. In contrast, Smart Polymer Composites (SPCs) are functional materials that respond to external stimuli by changing their chemical or physical properties in a repeatable way. These materials function as "synthetic skin" in plant health monitoring because they translate biological signals—such as volatile organic compounds—into measurable electrical or visual output.

***Author for Correspondence**
Kajal Kaul

[1,3,4]Associate Professor, Department of Information Technology, Bharati Vidyapeeth's College of Engineering, New Delhi, India
[2]Assistant Professor, Department of Information Technology, Bharati Vidyapeeth's College of Engineering, New Delhi, India
[5]Assistant Professor, Department of Computer Science, IMS Engineering College, Ghaziabad, Uttar Pradesh, India

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Conventional Approaches for Plant Health Assessment

The conventional approaches such as Visual Inspection, Microscopic analysis, serological tests like ELISA, molecular methods and other culture-based methods that have been used so far for detecting and assessing any plant diseases in farm fields are given in Table 1. Also, their sensitivity, specificity, cost, time and applicability are discussed in detail in Table 1.

Polymer Materials for Plant Health Assessment

Plant Health Assessment is of major concern and many polymer materials are used for that pursuit. There are various types of polymer materials for assessing plant health namely Natural polymers and Synthetic polymers. In this paper, we have discussed about these types and their role in Plant Health monitoring.

Natural Polymer Systems

Natural polymers like cellulose, chitosan, and alginate offer sustainable, biocompatible foundations for agricultural sensors. Cellulose provides a high surface area and is robust for sensor fabrication. Chitosan uses its abundant amino groups to immobilise biomolecules and capture pathogen-specific antigens. Alginate forms stable hydrogels through ionic crosslinking, creating a protective 3D network that preserves the stability of enzymes and antibodies in the field. In Table 2, Natural Polymers for Plant Health Assessment Applications are showcased as follows:

Synthetic Polymer Systems

Conductive polymers convert biological interactions into electrical signals via functionalization with antibodies, Poly-acrylates provide stimuli-responsive platforms and Siloxane-based polymers are suitable for wearable sensors.

Composite and Hybrid Polymer Materials

Composite and hybrid polymer materials combine the essence of natural and synthetic polymeric materials for enhancing the properties of plant disease detection. The discussion about Polymer-Nanoparticle Composites, Polymer-Metal Oxide Hybrid Systems and Carbon-Based Polymer Composites has been explicitly done in the paper.

Table 1. Comparison of conventional plant health assessment methods.

Method	Sensitivity	Specificity	Time to Result	Field applicability	Cost
Visual Inspection	Low	Medium	Immediate	High	Low
Microscopic Analysis	Medium	Medium	1-2 hours	Medium	Medium
Serological Tests (ELISA)	High	High	4-6 hours	Low	Medium
Molecular Methods (PCR)	Very High	Very High	2-4 hours	Low	High
Culture-Based Methods	Low	High	3-7 days	Low	Medium

Table 2. Natural polymers for plant health assessment applications.

Natural polymer	Key properties	Typical modifications	Disease identification applications
Cellulose [20, 24, 29, 33]	High strength, abundance	Oxidation, grafting, and nano-crystallization	Colorimetric sensors, test strips
Chitosan	Antimicrobial, cationic	Quaternization, crosslinking, nanoparticle formation	Electrochemical sensors, biosensors
Alginate	Gel-forming, biocompatible	Covalent crosslinking, composite formation	Hydrogel-based sensors, encapsulation systems
Starch [15]	Renewable, modifiable	Gelatinization, plasticization, grafting	Colorimetric indicators, biodegradable sensors
Silk fibroin	Mechanical strength, optical properties	Functionalization, blending	Optical sensors, wearable detection patches

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Polymer-Nanoparticle Composites

Polymer-nanoparticle composites create synergistic platforms that significantly enhance disease detection sensitivity. Gold and silver nanoparticles leverage localised surface plasmon resonance (LSPR) for colorimetric sensing; quantum dot composites provide superior photostability; and Magnetic nanoparticles, such as iron oxide, integrated into polymers help enable robust detection of pathogens. The combination of polymers with functional nanoparticles creates synergistic composites with enhanced sensing capabilities, leveraging the unique properties of both components. Table 3 represents Polymer-Nanoparticle Composites for Disease Detection as shown below:

Polymer-Metal Oxide Hybrid Systems

Polymer-metal oxide hybrids merge the processability of polymers with the specialised catalytic properties of metal oxides. Zinc oxide, Titanium dioxide, and Copper oxide composites are also used to detect pathogenic activity on plant leaf surfaces.

Carbon-Based Polymer Composites

Graphene-polymer composites, used in field-effect transistors (FETs), Carbon nanotube (CNT) hybrids and carbon black composites are used in resistive sensors; these devices detect infection by measuring resistance changes as the polymer swells upon exposure to volatile organic compounds (VOCs) released by diseased plants.

Polymer-Based Sensing Mechanisms

The polymer-based sensing mechanism uses hydrogels, cellulose, PMMA, PVA, thin polymer films, Ag/Au nanoparticle composites and microstructured polymers for sensing or monitoring plant health conditions.

Optical and Colorimetric Detection Mechanisms

Colorimetric sensors check pH-sensitive dyes or metal nanoparticles—within a polymer matrix to produce visible colour shifts. Fluorescence-based sensors provide even higher sensitivity and multiplexing capabilities by embedding quantum dots that alter intensity to biomarkers. Surface Plasmon Resonance (SPR) sensors facilitate label-free detection by measuring refractive index changes at metal-polymer interfaces. Table 4 shows the Object Detection Mechanisms in Polymer-Based Sensors.

Table 3. Polymer-nanoparticle composites for disease detection.

Nanoparticle type	Sensing mechanism	Polymer Matrix	Advantages
Gold/Silver	Colorimetric, LSPR	Chitosan, PVA	High sensitivity, visual readout
Quantum Dots	Fluorescence	PMMA, sol-gels	Multiplexing capabilities
Magnetic Iron Oxide	Magnetic separation	Hydrogels, PDMS	Sample pre-concentration
Upconversion Nanoparticles	Upconversion luminescence	PEG-based polymers	Near-IR excitation, low background
Carbon Nanodots	Fluorescence, electrochemical	PANI	Low toxicity, high quantum yield

Table 4. Object detection mechanisms in polymer-based sensors.

Mechanism	Detection principle	Sensitivity	Typical polymers used	Applications
Colorimetric	Visible color change	Moderate-High	Hydrogels, cellulose derivatives	Field test strips, visual indicators
Fluorescence	Emission intensity/wavelength shift	High	PMMA, PVA, sol-gels	Laboratory diagnostics, quantitative analysis
SPR	Refractive index changes	Very High	Thin polymer films, hydrogels	Label-free detection, real-time monitoring
SERS	Raman signal enhancement	Very High	Ag/Au nanoparticle [32] composites	Molecular fingerprinting, early detection
Interferometric	Optical path changes	High	Microstructured polymers	Multi-analyte detection

Principles of Electrical and Electrochemical Detection Mechanisms

In Smart Polymer composites, the principle of electrochemical sensing depends heavily on the redox reactions between the polymer matrix and the plant tissue. When certain phytohormones stick to the polymer surface, it results in the change of current or charge flow. This kind of response is exacerbated by embedding conducting fillers such as graphene or carbon nanotubes into the structures of polymer matrices. Electrical and electrochemical polymer systems provide rapid, highly sensitive detection compatible with portable field devices. Conductive polymer chemical resistors, Electrochemical biosensors, and field-effect transistor (FET) sensors offer a low-cost, flexible, and scalable solution for real-time monitoring.

Volatile Organic Compound (VOC)-Responsive Polymer Systems

Plants release certain volatile organic compounds (VOCs) for early disease prediction using signals monitored using polymer systems. Molecularly imprinted polymers (MIPs) act as synthetic receptors which study the texture of pathogen-induced VOCs. Electronic nose (e-nose) systems, polymer composites for algorithmic pattern detection and Stimuli-responsive hydrogels provide mechanical transduction by swelling or shrinking upon VOC exposure.

Polymer-Based Imaging and Indicator Platforms

The polymer-based imaging and indicator platforms include functional polymer films, coatings and smart polymer indicators and labels. These techniques are discussed in detail in the paper.

Functional Polymer Films and Coatings

Functional polymer coatings and thin films transform agricultural tools and plant surfaces into continuous health monitors. Equipment Smart coatings provide alerts through electrical shifts when detecting pathogens. Flexible thin-film sensors, Multilayer films identify elements from protective layers to ensure long-term durability in harsh environments.

Smart Polymer Indicators and Labels

Smart polymer indicators provide user-friendly monitoring for resource-limited settings. Colour-changing patches, Time-temperature integrators and Smart tags with wireless communication enable massive automated surveillance.

Data Interpretation and Signal Analysis Approaches

Table 5 shows the Data analysis approaches for the same as below:

Challenges and Material Design Considerations

The Key Challenges and Mitigation Strategies in Polymer-Based Disease Detection Systems are represented in Table 6 as follows:

Fabrication Techniques to develop Smart Polymer Techniques

We discussed certain mitigation strategies above. There are a few fabrication strategies that help to achieve precise control over the distribution of fillers. The techniques are as follows:

In-situ polymerisation, even before polymerisation, ensures a smooth blend of nanoparticles with monomers for uniformity; Thin-film sensors via Solution Blending and 3D printing help fabricate complex, biomimetic sensor shapes such as bio-composite leaf structures.

Table 5. Data analysis approaches for polymer-based disease detection systems.

Approach	Suitable sensor types	Advantages	Limitations	Typical applications
Pattern Recognition (PCA, LDA)	Multichannel systems	Data visualization, dimensionality reduction	Limited for nonlinear relationships	Disease fingerprinting
Deep Learning CNN [2, 5, 7, 10]	Imaging systems	Automatic feature extraction, high accuracy	Computational requirements	Image-based diagnostics
Signal Processing	Electrochemical sensors	Noise reduction, signal enhancement	Domain-specific knowledge	Real-time monitoring

RESEARCH METHODOLOGY

The workflow of the Research Methodology done in this paper is given in Figure 1 as follows:

Research Questions (RQs)

The Research Questions that arise pertaining to the role of bio-polymer composite for the controlled release of agrochemicals are as follows, as mentioned in Table 7, along with their Goal in the particular research paper.

Table 6. Key challenges and mitigation strategies in polymer-based plant disease detection systems.

Challenge	Impact on performance	Mitigation strategies	Research needs
Environmental Stability	Reduced sensitivity, shortened lifespan	Protective coatings, crosslinking, stabilizers	Long-term field validation
Selectivity	False positives/negatives	MIPs, specific receptors, sensor arrays	Recognition element development
Scalability	High production costs	Printing technologies, simplified designs	Manufacturing process optimization
User Accessibility	Limited adoption	Simple interfaces, smartphone integration	Human-centered design research
Regulatory Compliance	Market barriers	Biocompatible materials, thorough testing	Environmental impact studies

Table 7. Research questions.

Ref. No.	Research Question (RQ)	Goal
[1, 5, 7, 10]	RQ1: How can deep learning architectures (CNNs, U-Net, YOLO) be optimized for the automated detection and classification of plant diseases?	To establish a baseline for computer vision performance in identifying common pathogens like Late Blight, bacterial wilt, etc. using leaf imagery.
[6]	RQ2: Can real-time detection models like YOLOv8 be enhanced to increase accuracy in complex field environments?	To improve the speed and precision of automated scouting tools for farmers and precision agriculture applications.
[2]	RQ3: What is the efficacy of hyperspectral imaging compared to standard RGB imaging for early-stage virus detection?	To detect physiological changes in plants before symptoms are visible to the naked eye.
[3]	RQ4: How do molecular diagnostic tools like Multiplex PCR compare to image-based detection for bacterial pathogens?	To validate image-based findings with laboratory-grade biological confirmation of soft and brown rot.
[8–9]	RQ5: How can predictive modeling assist in developing effective fungicide spray schedules?	To transition from reactive disease management to proactive, weather-based forecasting to reduce chemical usage.
[11, 13, 19, 41]	RQ6: Can biopolymer-based coatings (whey protein, bio-nanocomposites) effectively extend the shelf life of plants post-harvest?	To reduce post-harvest losses and food waste using sustainable, edible preservation technologies.
[12, 17, 18, 39]	RQ7: What is the potential of valorising agricultural waste into circular economy bio-composites?	To promote sustainability by turning agricultural waste into high-value packaging or soil-enhancing materials.
[15, 16]	RQ8: How do starch-based bioplastics impact soil health and biodegradation under varying climate conditions?	To assess the environmental footprint of biodegradable plastics compared to traditional synthetic polymers.
[20–21, 23-24, 29, 32]	RQ9: How can natural polysaccharides serve as effective nanocarriers for agrochemicals?	To develop "green" delivery systems that encapsulate pesticides and fertilisers for safer handling and reduced runoff.
[22, 25, 30, 31, 35, 36]	RQ10: What are the socio-economic and environmental benefits of sustained-release agrochemical formulations?	To justify the adoption of nanotechnology in agriculture by highlighting long-term efficiency and reduced labour costs.
[26, 28, 33]	RQ11: Can stimuli-responsive nanocarriers achieve targeted delivery in the pathogen microenvironment?	To create "smart" delivery systems that only release active ingredients when specific triggers, like a fungal infection, are present.
[4, 14, 27, 34, 37–38, 40]	RQ12: What are the foundational properties of plant nutrition and material science that guide modern agricultural innovations?	To provide the fundamental chemical and nutritional context required for developing new varieties and storage technologies.

Quality Assessment Questions (QAs)

The Quality Assessment Attributes that arise based on the review done are given in Table 8 below:

Mapping Table of RQs with QAs

The mapping table of RQs with QAs based on the review done are given in Table 9 below:

LITERATURE REVIEW

The literature review of 41 papers is done and is represented in Table 10 as follows:

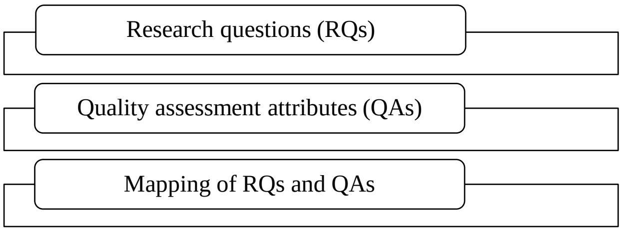

Figure 1. Research methodology workflow.

Table 8. Quality assessment attributes.

Quality assessment ID	Quality assessment attributes
QA1	Is the research objective clearly defined and aligned with the problem statement?
QA2	Is the methodology such as CNN architecture, experimental design described in sufficient detail for replication?
QA3	Are the datasets used clearly specified and of adequate size?
QA4	Are the performance metrics like mIoU, Accuracy, Dice Coefficient standard and clearly reported?
QA5	Does the paper compare its results against existing state-of-the-art methods?
QA6	Are the conclusions drawn supported by the results and statistical analysis provided?
QA7	Does the paper address environmental or real-world constraints such as uncontrolled backgrounds, lighting?
QA8	Is the source published in a reputable, peer-reviewed journal or high-impact conference?

Table 9. Mapping of research questions with quality assessment attributes.

Reference cluster	Reference numbers	RQs	Key QA focus
Computer vision/AI	1, 2, 5, 6, 7, 10	RQ1, RQ2, RQ3	QA1, QA3, QA4, QA5, QA8 (Metrics): Is the accuracy/Dice coefficient statistically significant?
Material science	11–19, 37, 38, 40, 41	RQ6, RQ7, RQ8, RQ12	QA1, QA2, QA8 (Methodology): Are the polymer ratios and synthesis steps reproducible?
Agrochemical delivery	20–36, 39	RQ9, RQ10, RQ11, RQ12	QA1, QA5, QA7, QA8 (Real-world): Does the controlled release work in actual soil/field conditions?
Field management	3, 4, 8, 9, 16	RQ4, RQ5, RQ8, RQ12	QA1, QA3, QA6, QA8 (Inference): Do the field trials support the long-term management claims?

Table 10. Literature review table.

Ref. No.	Core technology	Research focus
1	Fuzzy c-means/NN	Severity Estimation
2	Hyperspectral/FCN	Viral Detection
3	Multiplex PCR	Bacterial Pathogens
4	Biochemical Review	Human Health
5	CNN	Global Plant Health
6	YOLOv8/Attention	Real-time Detection
7	Deep Learning	Leaf Classification
8	Predictive Modeling	Weather-based Forecast

9	Spray Optimization	Disease Management
10	Deep Learning (VGG)	Severity Analytics
11	Biopolymers	Post-harvest Storage
12	Se-Nanocomposites	Biomass Growth
13	Bio-nanocomposites	Fruit/Veg Protection
14	Fiber Science	Material Mechanics
15	Starch Bioplastics	Biodegradation
16	Soil Science	Ecosystem Impact
17	Circular Economy	Packaging Recovery
18	Bio-composites	Waste Utilization
19	Natural Coating	Food Preservation
20	Polysaccharides	Sustained Release
21	Encapsulation	Delivery Kinetics
22	Nanocarriers	Socioeconomic Review
23	Engineered Nanocomposites	Plant Protection
24	Cellulose Matrix	Formulation Design
25	Block Copolymers	Soil Stability
26	Stimuli-Responsive	Targeted Delivery
27	Nano-clay Polymer	Nutrient Release
28	Advanced Polymers	Pesticide Logistics
29	Bio-polymers	Controlled Release
30	Nanotechnology	Agrochemical Delivery
31	Eco-nanocarriers	Sustainable Farming
32	Polysaccharides	Nano-Fertilizers
33	Dual-Responsive Gels	Smart Targeting
34	Green Chemistry	Multi-functional RF
35	Nano-Fertilizers	Nutrient Efficiency
36	Natural Matrices	Herbicide Control
37	Banana-Fiber-Reinforced Epoxy Composites	Mechanical Behaviour
38	Hybrid polymer composites	Mechanical Behaviour
39	Thermoplastic Composites	Waste Utilization
40	Epoxy composites reinforced with *Areca catechu* fiber	Mechanical Properties
41	Natural fibre composite materials	Review

RESULTS, CONCLUSION & FUTURE SCOPE

The Review Paper comprises 41 papers with emphasis on the core techniques used. The papers have been taken from Journals of good repute. Several approaches to plant health and effective disease management have been reviewed and cited in the Review table. Also, the Research Questions and Quality Assessment attributes have been mapped to analyse the key research areas and techniques. Optical, electrochemical, and VOC-responsive mechanisms aid in detecting plant diseases. AI, IoT, and advanced manufacturing transform these materials into robust systems in the polymer and composite fields. 3D printing and IoT integration for autonomous, real-time field monitoring. AI-driven multiplexed platforms will evolve from simple detection to comprehensive decision support, synthesizing sensor data with environmental context to manage simultaneous agricultural stressors.

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