Advanced Materials for Sustainable Agriculture: A Survey on Physical Coatings and Nanomaterials in Crop Protection

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Abstract

This survey paper explores the pivotal role of advanced materials, such as nanomaterials and biodegradable coatings, in promoting sustainable agriculture. These materials offer innovative solutions for enhancing crop protection, optimizing resource use, and minimizing environmental impacts. Nanotechnology has revolutionized agricultural inputs, providing nanofertilizers and nanopesticides that increase productivity while reducing ecological footprints. The integration of nanotechnology with biodegradable coatings enhances efficacy through controlled release mechanisms and improved mechanical properties, crucial for effective pest and disease management. The paper highlights the importance of Integrated Pest Management (IPM) strategies, where advanced materials enhance effectiveness and precision, reducing reliance on chemical pesticides and improving pest control methodologies. Despite their promise, challenges such as scalability, production, risk assessments, and environmental and ethical considerations persist. Addressing these requires continued research to optimize production techniques, improve data quality, and establish standardized measurement techniques. Future research should focus on optimizing formulations, novel synthesis methods, and robust categorization frameworks to ensure safe and effective integration of advanced materials into agriculture. By overcoming these challenges, the agricultural sector can fully harness the potential of advanced materials to enhance sustainability and productivity, contributing to global food security and environmental conservation.

1 Introduction

1.1 Challenges in Sustainable Agriculture

Sustainable agriculture encounters numerous challenges across environmental, economic, and social dimensions. Environmentally, ineffective pest management leads to significant crop losses and degradation, necessitating enhanced pest control strategies [1]. The rapid evolution of pathogens that can bypass genetic resistance complicates sustainable practices, particularly when relying on major resistance genes [2]. Additionally, crops' adaptation to abiotic stresses such as drought, salinity, and extreme temperatures poses substantial threats to productivity [3]. The potential toxicity of nanoparticles and the need for robust risk assessment frameworks for engineered nanomaterials further complicate their agricultural applications [4]. Moreover, traditional agricultural inputs are inefficient, and excessive chemical use causes environmental pollution, underscoring the urgent need for sustainable nutrient delivery and pest control methods [5]. The environmental pollution resulting from nitrogen fertilizer use, which elevates reactive nitrogen levels and harms natural resources, highlights the necessity for sustainable practices [6].

Economically, the high costs and lengthy development timelines for agrochemicals, coupled with stringent regulatory requirements, present significant barriers to maintaining crop yields under environmental stressors [7]. Integrating genetically engineered crops into existing Integrated Pest

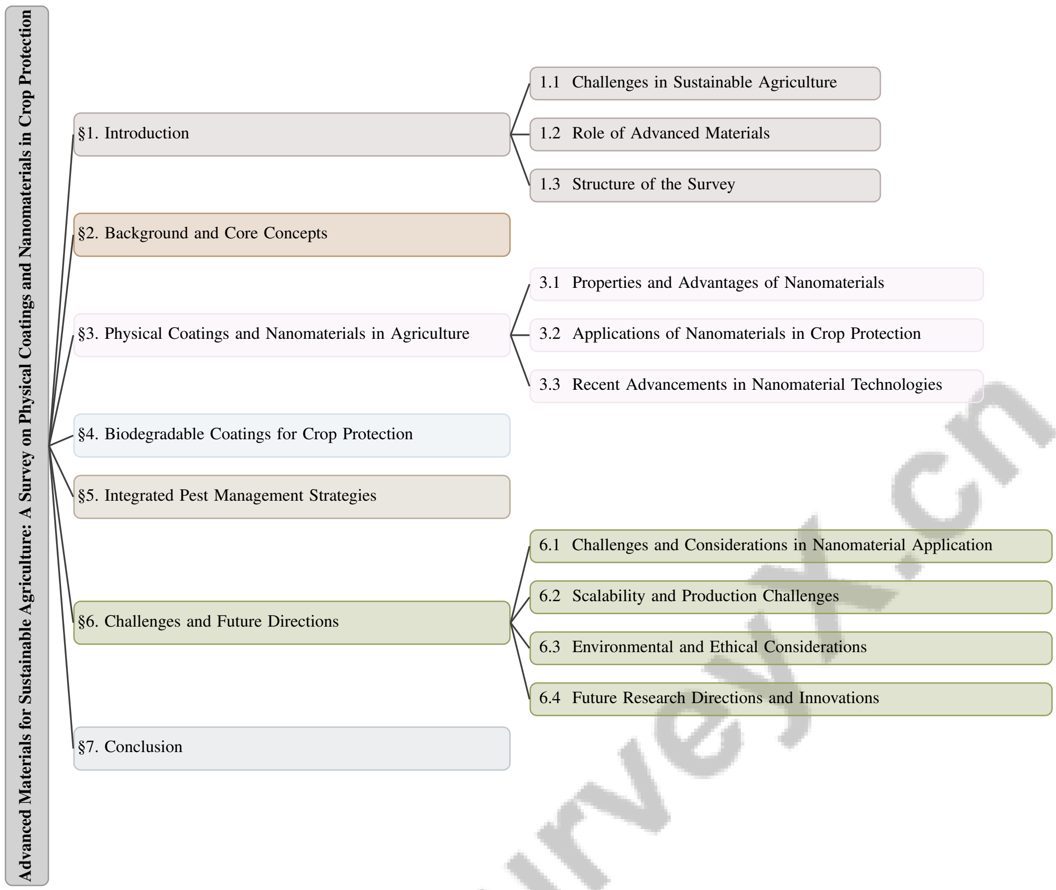

Figure 1: chapter structure

Management (IPM) frameworks is critical for sustainable pest management and resistance prevention [8]. However, economic barriers hinder the adoption of these technologies. The inefficiency of conventional agrochemicals, often leading to non-target toxicity, necessitates improved delivery systems and sustainable synthesis methods for nanomaterials [9]. Additionally, the demand for rapid and cost-effective soil analysis has grown, as traditional laboratory methods are often prohibitively expensive and time-consuming for smallholder farmers in emerging economies [10].

Socially, the low adoption of IPM practices among farmers remains a pressing concern, despite its significance for sustainable agriculture and climate change mitigation [11]. Effective pest management strategies that minimize pesticide use while ensuring crop health and yield are essential [12]. Classifying insect pests to prevent crop damage requires distinguishing between harmful and non-harmful species [13]. Moreover, the substantial impact of insect pests on global agricultural productivity underscores the need for real-time monitoring and management solutions [14]. Addressing these challenges necessitates an integrated approach leveraging advanced materials and innovative technologies to foster sustainable agricultural systems [15].

1.2 Role of Advanced Materials

Advanced materials play a pivotal role in addressing the multifaceted challenges of sustainable agriculture by enhancing crop protection, optimizing resource use, and minimizing environmental impacts. Nanotechnology has emerged as a transformative force, offering innovative solutions such as nanofertilizers, nanopesticides, and nanosensors that significantly enhance agricultural productivity while reducing ecological footprints [16]. For instance, non-transformative RNA interference (RNAi) delivery systems exemplify the innovative application of advanced materials, providing a cost-effective alternative to traditional transgenic methods by applying RNAi directly to crops [17].

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Nanomaterials, particularly metal oxide nanomaterials (MOx NMs), are increasingly utilized in the agri-food sector to meet the growing demands for sustainable food production and environmental protection [18]. The integration of nanotechnology in creating nanoparticles that encapsulate RNA enhances protection against degradation, thereby improving the efficacy of Spray-Induced Gene Silencing (SIGS) in crop protection [19]. This advancement highlights the potential of nanomaterials to revolutionize agricultural inputs by enhancing efficacy and sustainability [20].

Furthermore, combining Neosartorya fischeri antifungal proteins with rationally designed -core peptide derivatives represents a novel biofungicide strategy, showcasing the innovative application of bio-inspired materials in plant protection [21]. Designing synthetic materials inspired by biological systems significantly contributes to agriculture by addressing knowledge gaps in nanoscale physical properties of biomolecules and biomaterials, leading to more efficient practices [22].

Additionally, integrating deltamethrin into Long-Lasting Insecticidal Nets (LLINs), such as the ZeroFly net, demonstrates an innovative pest control approach, effectively managing pest populations in agricultural settings [23]. The rising need for sustainable pest control methods due to the environmental and health hazards associated with chemical pesticides underscores the potential of bacterial insecticides as effective alternatives [24]. Moreover, incorporating genetically engineered crops into diversified IPM strategies is essential for enhancing agricultural sustainability and food security while mitigating environmental impacts [8].

By harnessing the unique properties of advanced materials, including those offered by nanotechnology and bio-inspired designs, agriculture can achieve enhanced efficiency, sustainability, and resilience. The survey also addresses the challenges in risk assessment of engineered nanomaterials (ENMs) due to their novel properties and the rapid pace of product development [4]. Additionally, the need for actionable and trustworthy pest management strategies that bolster farmers' confidence in IPM is critical [11]. The integration of low-cost colorimetric paper sensors with AI-based analysis on smartphones facilitates high-resolution spatial mapping of soil pH, further exemplifying the innovative applications of advanced materials in agriculture [10]. Ultimately, these advancements contribute to the development of more sustainable and productive agricultural systems. Integrating farming awareness with pest control methods, advocating for a combined approach of chemical and biological controls, highlights the potential of advanced materials to support such strategies [1].

1.3 Structure of the Survey

This survey is systematically structured to explore the multifaceted role of advanced materials in sustainable agriculture, with a particular focus on physical coatings and nanomaterials for crop protection. The introduction comprehensively addresses critical challenges facing sustainable agriculture, including production losses due to pests, climate change, and resource depletion. It emphasizes the transformative potential of advanced materials, particularly nanotechnology, in mitigating these issues by enhancing food quality and safety, reducing reliance on chemical inputs, and improving nutrient absorption through innovative applications like nanofertilizers and nanopesticides. This sets the stage for discussing how these advanced materials can contribute to more resilient agricultural practices and food security in light of a growing global population [10, 25, 26, 16, 8].

Following the introduction, the survey delves into the background and core concepts, providing an overview of key terminologies and principles, including nanomaterials, biodegradable coatings, and IPM strategies. This section equips readers with foundational knowledge necessary to appreciate subsequent discussions.

The third section focuses on the application of physical coatings and nanomaterials in agriculture, highlighting their properties, advantages, and potential applications in crop protection. Recent advancements in nanomaterial technologies are explored, emphasizing innovative approaches that have emerged in recent years.

The survey then examines biodegradable coatings, discussing their environmental benefits and effectiveness in crop protection. This section also explores integrating biodegradable coatings with nanotechnology to enhance crop protection and highlights recent innovations in this domain.

IPM strategies are discussed in the fifth section, evaluating the role of advanced materials in enhancing IPM. This section provides examples of successful implementations, illustrating the practical benefits of integrating advanced materials into IPM frameworks.

The penultimate section addresses challenges and future directions in applying advanced materials in sustainable agriculture, discussing obstacles related to nanomaterial application, scalability, production, and environmental and ethical considerations. It concludes by identifying future research directions and potential innovations that could further advance the field.

The survey concludes by synthesizing key findings and insights, underscoring the critical role of advanced materials—such as colorimetric paper sensors and nanoparticle formulations—in enhancing sustainable agricultural practices. These innovations facilitate real-time soil analysis, improve pest management through genetically engineered crops, and optimize nutrient delivery, significantly contributing to food security and environmental protection amidst a growing global population [16, 8, 10]. This structured approach ensures a comprehensive understanding of the topic, guiding readers through the complexities and innovations in sustainable agriculture.The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Nanomaterials in Sustainable Agriculture

Nanomaterials play a pivotal role in enhancing sustainable agriculture by offering innovative solutions that boost crop productivity and resilience while mitigating environmental impacts. Their unique attributes, such as high surface area and reactivity, provide significant advantages over traditional agricultural inputs [16]. The development of nanostructured materials is essential due to their distinct properties compared to macroscopic counterparts, requiring advanced production techniques [27]. However, challenges like the instability and aggregation of metal oxide nanoparticles hinder their agricultural efficacy [28].

Nanotechnology has facilitated the creation of nanofertilizers and nanopesticides, optimizing agrochemical delivery and efficiency while reducing environmental contamination and enhancing resource use. The interactions of nanoparticles with biological systems, influenced by coating types and colloidal stability, are crucial for their agricultural effectiveness [29]. Despite this, concerns about the toxicity of engineered nanoparticles (ENPs) to plants and their environmental risks persist.

The surface functionalization of nanoparticles, through specific chemical group incorporation, significantly affects their interactions with plants and the environment, influencing efficacy and safety [30]. Addressing these issues requires comprehensive research to produce high-quality data and develop robust frameworks for assessing the environmental impact and technological feasibility of nanomaterials in agriculture [31]. The governance of nanomaterial innovation poses challenges due to their unique characteristics and complex industrial dynamics [31].

Recent advancements include using extracellular vesicles to protect and transport RNAs, enhancing RNA stability and uptake in Spray-Induced Gene Silencing (SIGS) for pest and disease management [19]. Additionally, machine learning techniques, like Digital In-line Holography (DIH), improve droplet field analysis in agricultural sprays, illustrating the integration of advanced technologies with nanomaterials to enhance agricultural practices. The potential of nanomaterials to promote sustainable agriculture through innovative applications that improve crop protection, optimize resource use, and minimize environmental impacts remains substantial. Continued exploration of their properties, interactions, and categorization is crucial for overcoming current challenges and advancing their integration into sustainable agriculture.

2.2 Biodegradable Coatings and Crop Protection

Biodegradable coatings offer promising solutions in sustainable agriculture by reducing reliance on conventional pesticides and minimizing environmental impact. Derived from natural and synthetic biodegradable materials, these coatings form protective barriers on plant surfaces, mitigating pest infestations and diseases while decomposing into non-toxic byproducts [32]. They significantly reduce soil and water contamination risks associated with traditional agrochemicals, promoting healthier ecosystems [33].

Integrating biodegradable coatings with nanotechnology enhances their efficacy in crop protection. Nanotechnology enables the development of coatings with improved mechanical properties, controlled release of active ingredients, and enhanced adhesion to plant surfaces [26]. This synergy between

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biodegradable materials and nanoscale engineering optimizes agrochemical delivery and performance, ensuring effective pest and disease control while minimizing environmental footprints [34]. However, the complex interactions between nanomaterials and biological systems necessitate rigorous safety assessments to address potential toxicity and environmental exposure risks.

Recent advancements in biodegradable coatings include novel dispersion methods that produce monodisperse nanoparticles, enhancing the uniformity and functionality of these coatings [27]. The application of metal oxide nanomaterials (MOx NMs) in biodegradable coatings has shown transformative potential in improving agricultural productivity and food safety, highlighting the role of advanced materials in sustainable agriculture [18]. Despite these advancements, challenges persist in the synthesis and stability of magnetic nanoparticles (MNPs) and other nanomaterials used in biodegradable coatings, particularly regarding biocompatibility and effective delivery within biological systems [35]. Ongoing research and development are essential to optimize the properties of biodegradable coatings and ensure their safe and effective application in agriculture. As the demand for sustainable agricultural practices grows, biodegradable coatings offer a viable solution for enhancing crop protection while safeguarding environmental health.

2.3 Integrated Pest Management (IPM) Strategies

Integrated Pest Management (IPM) is a strategic approach to pest control that emphasizes the integration of multiple methodologies to manage pest populations sustainably and economically. Unlike single-method strategies, IPM incorporates biological, cultural, and chemical methods to enhance efficacy and improve crop yield. The principles of IPM are based on continuous monitoring of pest populations and the use of decision support systems to identify the most effective and least disruptive control measures [36].

A fundamental component of IPM is the use of biocontrol agents, which utilize natural predators or pathogens to suppress pest populations, thereby decreasing reliance on chemical pesticides and minimizing environmental impact [15]. This approach not only addresses immediate pest threats but also contributes to long-term agricultural sustainability by fostering resilient ecosystems. The strategic incorporation of resistant crop varieties and chemical controls, such as the sustained release of insecticides like deltamethrin from treated netting, provides ongoing protection against pests [1].

Nanotechnology offers innovative applications within IPM frameworks, enhancing the precision and efficacy of pest control measures. The surface chemistry of nanoparticles can be engineered using specialized coatings, such as statistical copolymers with functional groups that enhance binding affinity and stability. This tailoring process significantly improves cellular uptake and biological responses, ultimately increasing the efficacy of nanopesticides. By manipulating chemical properties at the nanoscale, researchers can enhance interactions between nanoparticles and biological systems, allowing for targeted delivery and reduced toxicity, thereby maximizing benefits while minimizing potential health risks associated with nanoparticle exposure [28, 31, 37]. However, the complexity and potential unforeseen outcomes of engineered nanomaterials interacting with biological systems necessitate careful evaluation and categorization to ensure their safe application in IPM.

Integrating these diverse strategies into a cohesive IPM framework is crucial for managing complex pest challenges, such as the fall armyworm, where a combination of biological, cultural, and chemical controls has proven effective. This comprehensive approach addresses immediate pest threats and contributes to long-term agricultural sustainability by reducing chemical inputs and fostering resilient ecosystems. Successful IPM implementation requires categorizing existing methods into stages of awareness, technology transfer through workshops, field trials, and ongoing monitoring of pest populations and biocontrol agents [15].

Despite its advantages, IPM effectiveness is often challenged by factors such as farmers' skepticism regarding its efficacy compared to conventional pesticides, leading to reluctance in adopting these practices. Increasing farmers' awareness and understanding of IPM's benefits can lead to improved pest management practices, thereby reducing reliance on chemical pesticides and enhancing the effectiveness of biological control methods [15]. As sustainable agriculture evolves, the role of IPM strategies in promoting environmentally friendly and effective pest management remains indispensable.

In recent years, the integration of advanced materials into agricultural practices has garnered significant attention. This shift is largely attributed to the potential benefits offered by nanomaterials and physical coatings. To illustrate this concept, Figure 2 presents a comprehensive overview of the hierarchical structure of these materials in agriculture. The figure emphasizes their diverse properties and applications in crop protection, alongside recent technological advancements. Notably, it highlights how the incorporation of nanomaterials and advanced delivery systems can enhance agricultural practices. Moreover, the figure addresses the challenges and optimizations necessary for promoting sustainable agricultural practices, thereby providing a holistic view of the future of agriculture in the context of material science.

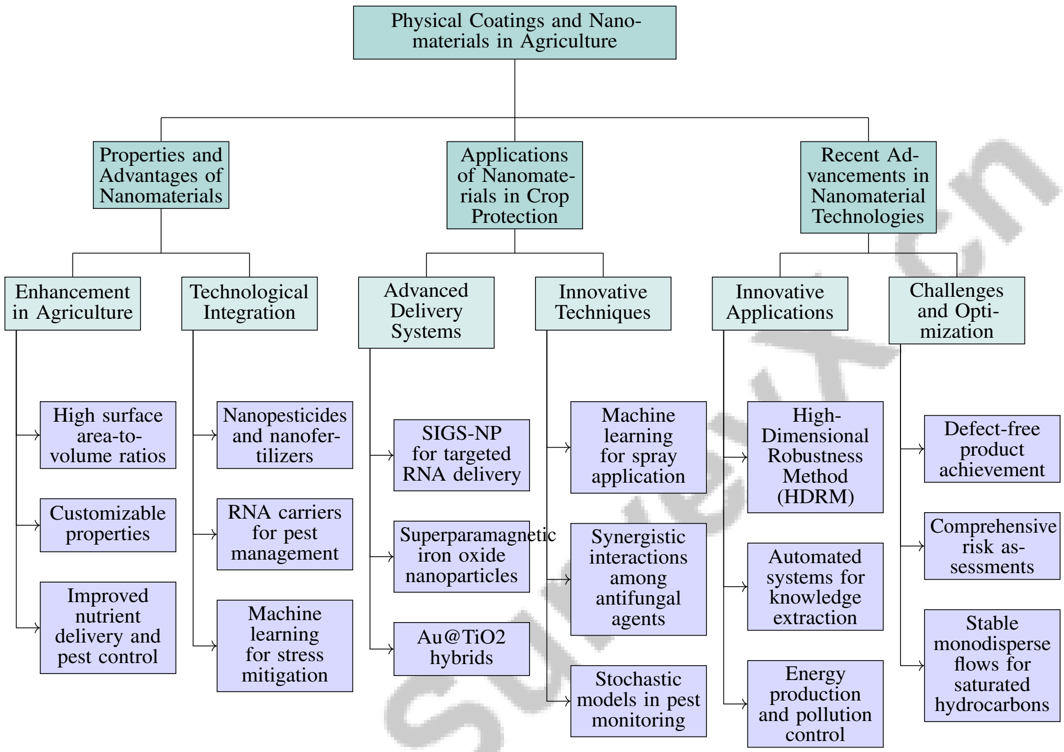


Figure 2: This figure illustrates the hierarchical structure of physical coatings and nanomaterials in agriculture, emphasizing their properties, applications in crop protection, and recent technological advancements. It highlights the enhancement of agricultural practices through nanomaterials, advanced delivery systems, and innovative techniques, while also addressing challenges and optimizations for sustainable agricultural practices.

3 Physical Coatings and Nanomaterials in Agriculture

3.1 Properties and Advantages of Nanomaterials

Nanomaterials, characterized by high surface area-to-volume ratios and customizable properties, hold significant potential for enhancing crop protection and productivity in agriculture [38]. Their modular structure allows seamless integration into agricultural systems, facilitating the development of nanopesticides and nanofertilizers that improve nutrient delivery and pest control [5, 39]. The synthesis and characterization of these materials, including carbon-based variants, are crucial for food safety and environmental remediation [39]. Predictive models for nanomaterial synthesis aid in optimizing their properties for agricultural applications, thereby enhancing efficacy and minimizing risks [31, 36].

Nanomaterials also serve as efficient RNA carriers, offering specific and environmentally friendly alternatives to traditional pest management [5]. The integration of machine learning techniques further refines their application in stress mitigation and crop productivity [36]. Methods like NPCoronaPredict combine simulations with data-driven approaches to predict corona composition, essential for understanding nanomaterials' properties [40]. These versatile properties establish nanomaterials as transformative tools in sustainable agriculture, enhancing nutrient delivery and pest control while minimizing environmental impacts [6].

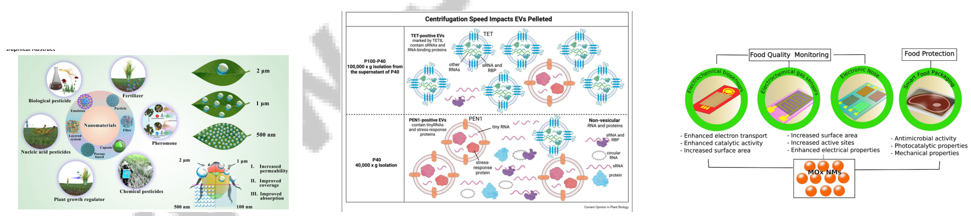
3.2 Applications of Nanomaterials in Crop Protection

Method Name	Technological Integration	Delivery Systems	Environmental Impact
SIGS-NP[19]	Nanotechnology	Nanoparticle Carriers	Lower Dosages
ML-DIH[41]	Machine Learning	-	-
DBN[12]	-	-	Reduce Pesticide Treatments
ISAR[3]	Machine Learning Methods	Nanomaterials For Seed	Efficient Pest Control

Table 1: Comparison of technological integration, delivery systems, and environmental impact across various methods utilizing nanomaterials and machine learning in crop protection. The table highlights the diverse applications and benefits of these methods, such as enhanced precision in pest control and reduced environmental impact.

Nanomaterials revolutionize crop protection through advanced agrochemical delivery systems that enhance the precision of pest and disease control [16]. For instance, SIGS-NP facilitates targeted RNA delivery to plant surfaces, bolstering protection against pathogens [19]. Superparamagnetic iron oxide nanoparticles (MNPs) and Au@TiO2 hybrids exemplify the use of nanomaterials in efficient delivery systems and crop protection, respectively [42, 43]. Machine learning techniques, such as modified U-Net and VGG16 classifiers, enhance spray application accuracy, optimizing nanomaterials' pest control efficacy [41]. Table 1 provides a comprehensive comparison of different methods incorporating nanomaterials and machine learning for crop protection, detailing their technological integration, delivery systems, and environmental impact.

Synergistic interactions among antifungal agents facilitated by nanomaterials enable effective fungal infection control at lower dosages, reducing environmental impact [21]. Stochastic models in pest monitoring networks (PMNs) underscore nanomaterials' role in refining pest management strategies [12]. Imogolite nanotubes and InsectNet further demonstrate nanomaterials' diverse applications in crop protection and pest management [44, 14]. Experiments with nanoparticle-treated maize seeds have shown improved resilience under stress, highlighting nanomaterials' potential in enhancing plant resilience [3]. Their adaptability underscores their pivotal role in advancing sustainable agricultural practices [39].



(a) Advancements in Nanomaterials for Agriculture: Enhancing Plant Growth and Pesticide Delivery[20]

(b) Centrifugation Speed Impacts EVs Pelleted[19]

(c) Food Quality Monitoring and Protection[18]

Figure 3: Examples of Applications of Nanomaterials in Crop Protection

As shown in Figure 3, nanomaterials' integration into agriculture marks a transformative approach to crop protection, addressing plant growth and pest management challenges. The section on "Physical Coatings and Nanomaterials in Agriculture: Applications of Nanomaterials in Crop Protection" illustrates nanotechnology's multifaceted role in enhancing agricultural practices. The figures highlight how nanomaterials optimize delivery systems, impacting plant cell biology and nutrient delivery, and ensuring food safety through advanced monitoring systems [20, 19, 18].

3.3 Recent Advancements in Nanomaterial Technologies

Recent advancements in nanomaterial technologies have propelled innovative agricultural applications, promoting crop protection and environmental sustainability. Table 2 provides a comprehensive

Method Name	Application Areas	Optimization Techniques	Safety and Risk Assessment
HDRM[45]	Environmental Sustainability	Parameter Refinement	Risk Assessment
CDM[27]	Saturated Hydrocarbons	Process Optimization	-

Table 2: Overview of recent methodologies in nanomaterial technologies, highlighting their application areas, optimization techniques, and approaches to safety and risk assessment. This table presents a comparison of the High-Dimensional Robustness Method (HDRM) and a method for saturated hydrocarbons, illustrating their contributions to environmental sustainability and process optimization.

comparison of recent methodologies in nanomaterial technologies, focusing on their application areas, optimization techniques, and safety and risk assessment strategies. The High-Dimensional Robustness Method (HDRM) models dose-response kinetics, crucial for understanding nanomaterials' interactions with biological systems, supporting safer use and reducing reliance on traditional testing methods [45]. Optimizing nanomaterials' mechanical properties, refining processing parameters, and exploring new materials are critical for enhancing their performance in agriculture [46]. Automated systems for knowledge extraction expedite innovation, facilitating efficient nanomaterial synthesis and application [47].

Nanomaterials' environmental benefits are notable in promoting sustainability and efficiency, particularly in energy production and pollution control [48]. However, achieving defect-free products and optimizing properties for specific agricultural uses remain challenges [49]. Comprehensive risk assessments are necessary to ensure safe and effective nanomaterial use in agriculture, balancing benefits and risks [25, 31].

New methods for producing nanomaterials, especially for saturated hydrocarbons, have achieved stable monodisperse flows, ensuring consistent quality in agricultural applications [27]. As research advances, optimizing nanomaterials and developing innovative applications will be vital for sustainable agricultural practices and addressing global food security challenges.

4 Biodegradable Coatings for Crop Protection

4.1 Environmental Benefits of Biodegradable Coatings

Biodegradable coatings, composed of natural and synthetic materials, decompose into non-toxic byproducts, reducing soil and water contamination and fostering a healthier ecosystem [50]. Their eco-friendliness and cost-effectiveness make them suitable for large-scale production, addressing both environmental sustainability and economic viability [50]. By integrating these coatings with RNA interference (RNAi) delivery systems, crop protection efficacy is enhanced while ecological footprints are reduced [17]. This approach minimizes reliance on chemical pesticides and supports soil health and biodiversity. Starch-based coatings optimize nutrient delivery by improving the release time and mechanical strength of fertilizers, thereby mitigating environmental pollution from excessive fertilizer use [6]. Innovations such as plant protein-enabled biodegradable triboelectric nanogenerators further enhance crop growth through electric fields, ensuring biodegradability and sustainability [51].

4.2 Effectiveness in Crop Protection

Benchmark	Size	Domain	Task Format	Metric
NMPB[52]	46,800	Nanomaterials	Morphology Prediction	Accuracy, F1-score
pH-MAP[10]	805	Soil Chemistry	Soil PH Measurement	Accuracy, Turnaround Time

Table 3: This table presents a summary of key benchmarks relevant to the domain of crop protection, highlighting their respective sizes, domains, task formats, and evaluation metrics. The benchmarks include NMPB, which focuses on morphology prediction within the nanomaterials domain, and pH-MAP, which addresses soil pH measurement in soil chemistry. The metrics used for evaluation include accuracy, F1-score, and turnaround time, providing a comprehensive overview of the benchmarks' scope and applicability.

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Biodegradable coatings effectively deliver active ingredients while minimizing environmental impact, often utilizing natural materials like A-type starch to enhance the adherence of protective agents on plant surfaces [50]. Their use in agriculture reduces reliance on chemical pesticides, promoting sustainable crop protection strategies. These coatings enhance antifungal efficacy through synergistic interactions, allowing for reduced dosages of active ingredients, thus lowering environmental contamination risks and mitigating pest resistance [21]. Machine learning-based Digital In-line Holography (DIH) optimizes agricultural spray applications, achieving high droplet extraction accuracy and enhancing precision agriculture [41]. Optimizing Pest Monitoring Networks (PMNs) through strategic spatial density adjustments significantly reduces pesticide applications, enhancing crop protection by ensuring treatments are applied only when necessary, conserving resources, and minimizing environmental impact [12]. The integration of biodegradable coatings with innovative technologies and strategic pest management practices enhances crop protection, leveraging plant proteins and advanced characterization techniques to offer sustainable solutions for pest and disease management [20, 51, 5, 25, 26]. Table 3 provides a detailed overview of representative benchmarks utilized in the field of crop protection, illustrating their application to various domains and the metrics employed for their evaluation.

4.3 Integration with Nanotechnology

The integration of biodegradable coatings with nanotechnology advances crop protection by enhancing efficacy and environmental sustainability. By combining nanomaterials with biodegradable matrices, these coatings achieve superior physical, mechanical, and biological characteristics essential for agricultural applications [32]. The synergy between nanomaterials and bio-based materials utilizes the high surface area-to-volume ratio of nanoparticles, enabling efficient delivery of active ingredients and improved adherence to plant surfaces [50]. Innovations like multidentate binding of phosphonic acids during the coating process significantly enhance adhesion and stability, ensuring controlled release of agrochemicals and reducing environmental contamination [28]. The development of a morphology index provides insights into optimizing hybrid coatings for specific applications [50]. This integration facilitates advanced functionalities, such as responsiveness to environmental stimuli, enhancing precision in crop protection strategies. As demand for sustainable agricultural practices grows, this approach offers promising solutions for enhancing crop protection, improving agrochemical delivery efficiency, and minimizing ecological footprints [20, 5, 25, 26, 16].

4.4 Innovations in Biodegradable Coatings

Recent advancements in biodegradable coatings focus on improving functionality and environmental compatibility for sustainable agriculture. Novel dispersion methods for producing monodisperse nanoparticles enhance the uniformity and functionality of biodegradable coatings [27]. These methods allow precise control of particle size and distribution, optimizing coating performance in agricultural applications. The integration of biodegradable coatings with advanced nanomaterials, such as metal oxide nanomaterials (MOx NMs), enhances mechanical properties and adhesion while providing controlled release mechanisms for active ingredients, reducing reapplications and minimizing environmental impact [18]. Starch-based coatings improve fertilizer release time and mechanical strength, optimizing nutrient delivery and reducing pollution [6]. Innovations also focus on biodegradability and ecosystem compatibility, exemplified by plant protein-enabled biodegradable triboelectric nanogenerators, which enhance crop growth through electric fields while maintaining sustainability [51]. The incorporation of technologies like RNA interference (RNAi) delivery systems into biodegradable coatings offers targeted pest and disease management, minimizing environmental footprints while protecting crops [17]. As demand for environmentally friendly solutions rises, these innovations present a viable path toward sustainable crop protection and enhanced agricultural productivity.

5 Integrated Pest Management Strategies

5.1 Principles and Practices of IPM

Integrated Pest Management (IPM) is a holistic strategy emphasizing sustainable pest control by integrating diverse methods to minimize environmental and economic impacts. Central to IPM is the utilization of natural predators, parasitoids, and pathogens for biological control, complemented by cultural, mechanical, and chemical techniques to enhance pest suppression and crop yield [53]. Mathematical models, including ordinary and impulsive differential equations, enable the analysis of pest dynamics and the evaluation of control strategies, providing robust predictions and actionable insights through causal inference and counterfactual explanations [54, 11].

IPM strategies are classified by sustainability, effectiveness, and adherence to IPM principles, focusing on immediate pest threats and long-term agricultural resilience [55]. The evolution of these strategies, documented across regions, categorizes research into chemical, biological, and agronomic controls, demonstrating IPM's adaptability [56]. Collaboration between universities and farmers facilitates IPM implementation through knowledge transfer [57]. Technological advancements, such as machine learning and decision support systems, enhance IPM, with tools like InsectNet improving real-time pest identification [14]. The integration of causal models fosters trust in pest management decisions [11]. Categorizing plant diseases by phytopathogen type allows for targeted interventions, reducing chemical pesticide reliance and promoting timely pest responses [58].

5.2 Role of Advanced Materials in Enhancing IPM

Advanced materials significantly enhance IPM by reducing chemical pesticide reliance and improving pest control. Genetically engineered crops offer pest resistance and herbicide tolerance, essential for a diversified IPM plan. Community engagement in knowledge-sharing bolsters adoption, promoting sustainability and minimizing non-target organism impact [8, 57, 55]. Nanomaterials exemplify this advancement, offering targeted delivery systems that enhance biological control and reduce environmental impact. Nanoparticles improve pheromone-based strategies by controlling release rates, enhancing IPM efficacy while warranting further research on potential health risks [2, 36].

Biodegradable coatings with nanotechnology enable controlled release mechanisms, reducing reapplication needs and enhancing pest management efficacy. Bacterial insecticides, categorized by target pests and action modes, emphasize specificity and safety [11]. Advanced materials address challenges like phytopathogen evasion and crop disease prevalence, reducing economic losses and enhancing productivity [14]. Future research should integrate machine learning to predict nanoparticle toxicity, reducing traditional experiment reliance [36]. Active learning and saliency techniques can optimize pest management datasets, enhancing advanced materials' application in IPM. These materials provide innovative solutions that promote sustainable practices and improve pest management efficacy.

5.3 Case Studies and Successful Implementations

The integration of advanced materials in IPM has led to successful implementations enhancing agricultural sustainability. Nanomaterials in nanopesticides leverage high surface area and controlled delivery to improve pest control while minimizing environmental impact, enhancing active ingredient stability and reducing pollution and costs [5, 20, 48]. In crop protection, nanomaterials combined with antifungal proteins create biofungicides that protect against pathogens, offering a sustainable alternative to traditional fungicides [21].

Biodegradable coatings with nanotechnology create protective plant barriers, reducing pest infestations and disease incidence. These coatings align with IPM strategies by conserving natural enemies and biodiversity, promoting healthier ecosystems [57, 55, 21, 8, 53]. Machine learning and AI advancements, such as AI-based models and InsectNet, optimize pest control and reduce pesticide use, enhancing monitoring accuracy and efficiency [14].

These case studies highlight advanced materials and technologies' transformative potential in IPM, showcasing innovations like genetically engineered crops, data analysis frameworks, and mobile soil analysis systems that reduce environmental impact and enhance pest control [8, 11, 10, 55]. Continued research is essential to refine these technologies and expand their applications across diverse agricultural contexts.

6 Challenges and Future Directions

6.1 Challenges and Considerations in Nanomaterial Application

The application of nanomaterials in agriculture faces multiple challenges, including an incomplete understanding of their long-term biocompatibility and potential toxicity, particularly for 2D nanomaterials [38]. The lack of standardized methods for toxicity assessment, coupled with complex interactions between nanoparticles and biological systems, complicates comprehensive evaluations [30]. Variability in nanoparticle toxicity and uptake, influenced by surface characteristics, further complicates safety assessments, while limited knowledge of their long-term environmental impacts hinders widespread adoption [5]. The absence of standardized categorization procedures may lead to oversimplified safety assumptions, complicating risk assessment and regulatory processes [31].

Scalability and uniformity in producing high-purity carbon nanomaterials remain challenging, limiting their agricultural applications [39]. Although machine learning approaches hold promise for predicting nanomaterial behavior, issues related to data quality and model interpretability affect prediction reliability [36]. The extraction of structured knowledge from multimodal scientific literature is a significant challenge, impeding the development of comprehensive databases for nanomaterial applications [47].

Environmental factors such as humidity and film thickness significantly influence the performance of plant protein-enabled biodegradable triboelectric nanogenerators, necessitating robust design and testing under variable conditions [51]. The assumption that farmers will engage with awareness programs may not hold true, complicating the adoption of nanomaterial-based solutions [1]. Additionally, time delays introduce complexity for real-time decision-making, further complicating practical implementation [15].

Addressing these challenges requires optimizing nanomaterial properties, improving data quality, and establishing standardized measurement techniques. Addressing agricultural challenges, including climate change and resource management, can enable the effective leveraging of nanomaterials to enhance sustainable practices, improve fertilizer and pesticide efficiency through targeted delivery, reduce chemical waste, and increase crop yields while mitigating potential risks to human health and the environment [20, 5, 25].

6.2 Scalability and Production Challenges

Scalability and production of advanced materials for agricultural applications present significant challenges. Computational complexity and resource demands of existing algorithms limit their applicability in real-time scenarios and hinder integration into large-scale agricultural systems [59]. This is compounded by challenges related to reproducibility of particle sizes in larger production settings, as seen in nanostructured materials development [27].

Current research often neglects the scalability of nanotechnology applications, particularly concerning the long-term effects of nanomaterials in biological systems, which is vital for their safe deployment in agriculture [60]. The production of high-purity nanomaterials, such as carbon nanomaterials, faces obstacles related to scalability and uniformity, limiting their agricultural applications [39].

Moreover, reliance on precise input parameters and models, exemplified by the NPCoronaPredict method, poses limitations for nanoparticle application scalability, as these parameters may not be universally available for all biomolecules or novel nanoparticle designs [40]. This underscores the need for robust and adaptable production processes that can meet the diverse and evolving requirements of advanced materials in agriculture.

To effectively tackle scalability and production challenges, a coordinated approach is essential, focusing on optimizing production techniques, enhancing computational models through advanced machine learning and AI methods, and ensuring reproducibility and consistency of nanomaterials. This includes leveraging large datasets for accurate morphology predictions, employing natural language processing and computer vision to extract insights from extensive materials science literature, and utilizing machine learning to streamline design and synthesis processes, thereby accelerating the development and application of novel functional nanomaterials [61, 47, 52]. By overcoming these obstacles, the agricultural sector can effectively harness advanced materials to enhance productivity and sustainability, contributing to global food security and environmental conservation.

6.3 Environmental and Ethical Considerations

The use of advanced materials in agriculture raises environmental and ethical considerations that must be addressed to ensure responsible use. A primary environmental concern is the potential impact of nanomaterials on ecosystems, particularly regarding their persistence and bioaccumulation in soil and water systems. The release of engineered nanomaterials (ENMs) into the environment can lead to unforeseen ecological consequences, necessitating comprehensive risk assessments and robust frameworks for evaluating their environmental impact [4]. Categorizing nanomaterials based on their physicochemical properties and exposure potential is critical for understanding and mitigating these risks [31].

Ethically, the use of advanced materials in agriculture raises questions about the equitable distribution of benefits and risks. The potential for these technologies to exacerbate disparities between resource-rich and resource-poor regions is a significant concern, as the high costs and technical expertise required for implementation may limit access for smallholder farmers in developing countries [10]. This disparity underscores the need for policies that promote inclusive access to advanced agricultural technologies and ensure equitable sharing of benefits across socio-economic groups.

Furthermore, the governance of nanomaterial innovation poses ethical challenges, as the rapid pace of technological advancement often outstrips the development of regulatory frameworks and public understanding [31]. Ensuring transparency and public engagement in the development and deployment of these technologies is essential to build trust and address societal concerns about their safety and ethical implications.

The potential human health risks associated with nanomaterials in agriculture also warrant ethical consideration. The limited understanding of the long-term health effects of exposure to nanoparticles necessitates precautionary measures and rigorous safety evaluations to protect agricultural workers and consumers [36]. Ethical considerations must also address the potential for unintended consequences, such as resistance development in pest populations, which could undermine the long-term sustainability of pest management strategies.

6.4 Future Research Directions and Innovations

To advance the field of advanced materials for sustainable agriculture, a comprehensive research agenda emphasizing technological innovation and environmental stewardship is essential. Future research should prioritize optimizing nanoparticle coatings and exploring additional biodegradable materials to enhance controlled-release fertilizers, thereby improving nutrient delivery while minimizing environmental impacts [6]. The exploration of novel synthesis methods and the development of effective sorting techniques for carbon nanomaterials are essential for expanding their applications in emerging agricultural technologies [39].

The governance of nanomaterials necessitates specific downstream policies and interventions to ensure their safe and sustainable integration into agricultural systems. Future work should focus on developing robust categorization frameworks that incorporate new scientific findings, enhancing regulatory clarity, and ensuring comprehensive risk assessments [31]. This includes developing standardized protocols for evaluating the biocompatibility of 2D nanomaterials and exploring their applications in emerging biomedical fields, which could provide insights into their broader applicability in agriculture [38].

Research should also aim to expand the types of material characterization graphs that can be processed, indicating a direction for nanomaterial application research [47]. Additionally, refining models to incorporate dynamic factors affecting pest management and exploring strategies to enhance farmer awareness are critical for improving integrated pest management (IPM) strategies [15]. Future research could investigate incorporating time delays in awareness effects and the dynamics of infected versus uninfected crop populations, providing a nuanced understanding of pest management dynamics [1].

In crop protection, identifying optimal combinations of resistance loci is essential for developing durable quantitative resistance strategies. Improving the interpretability of IPM models and broadening their application across various crops and geographical regions can significantly enhance farmers' confidence in IPM strategies. Utilizing advanced data analysis frameworks that provide transparent pest predictions, actionable insights, and robust treatment effect assessments will empower farmers to better understand the effectiveness of IPM practices. This, combined with effective communication and knowledge-sharing initiatives, can bridge the existing trust gap and promote the adoption of eco-friendly pest management solutions [11, 3, 57]. This involves refining frameworks and incorporating spatial dynamics into mathematical models to improve predictions of pest population trends and control strategies.

Future research should focus on developing advanced coating systems that address current limitations, including smart coatings that respond to environmental stimuli and novel processing techniques for thicker coatings [51]. Optimizing copolymer synthesis and exploring applications in other nanoparticle types can inform future innovations in sustainable agriculture. By addressing these research priorities, the field can continue to innovate and contribute to global agricultural sustainability, ensuring that advanced materials are utilized effectively and responsibly to enhance crop productivity and environmental health.

7 Conclusion

Advanced materials, particularly nanomaterials and biodegradable coatings, are instrumental in advancing sustainable agricultural practices. Their innovative applications in crop protection and resource optimization are pivotal in reducing environmental impacts. Nanomaterials, with their distinct physicochemical properties, have revolutionized agricultural inputs like nanofertilizers and nanopesticides, enhancing productivity while minimizing ecological footprints. The integration of nanotechnology with biodegradable coatings further amplifies their utility, offering controlled release and improved mechanical properties crucial for effective pest and disease management.

The survey highlights the critical role of Integrated Pest Management (IPM) strategies, where advanced materials significantly enhance precision and effectiveness. By reducing dependency on chemical pesticides and refining pest control techniques, these materials bolster the sustainability and resilience of agricultural systems. Their successful incorporation into IPM frameworks underscores their transformative potential in mitigating environmental impacts and improving pest management efficacy.

Despite these advancements, challenges remain in the application of advanced materials in agriculture. Issues such as the scalability and production of nanomaterials, the need for comprehensive risk assessments, and environmental and ethical concerns require attention. Continued research is essential to optimize production techniques, improve data quality, and establish standardized protocols.

Future research should focus on refining formulations, exploring novel synthesis methods, and developing robust categorization frameworks to ensure the safe and effective integration of advanced materials into agricultural systems. By addressing these challenges, the agricultural sector can fully exploit the potential of advanced materials, enhancing sustainability and productivity, and ultimately contributing to global food security and environmental conservation.

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