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Nano-Enabled Spray-Induced Gene Silencing: A Promising Strategy for Managing Emerging and Established Plant Diseases in Nigeria

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ABSTRACT

Crop production in Nigeria is increasingly threatened by insect pests, nematodes, fungi, bacteria, and viruses, resulting in substantial yield losses and compromised food security. Conventional chemical pesticides and fungicides remain the primary control measures, however, their prolonged use has contributed to environmental pollution, health concerns, and the emergence of resistant pest and pathogen populations. This review aims to evaluate the potential of nano-enabled Spray-Induced Gene Silencing (SIGS) as a sustainable and precise strategy for managing emerging and established plant diseases and pests in Nigeria. Spray-Induced Gene Silencing employs exogenous double-stranded RNA (dsRNA) to silence essential genes involved in pathogen virulence or pest survival. Recent advances in nanotechnology have significantly enhanced SIGS by incorporating nanocarriers, including lipid nanoparticles, polymeric nanoparticles, and bioclay nanosheets, which protect dsRNA from degradation, improve plant surface penetration, enable controlled release, and increase target specificity. Evidence from global and African studies demonstrates that nano-enabled SIGS effectively suppresses economically important pests and pathogens while minimizing adverse effects on non-target organisms and reducing reliance on synthetic pesticides. Integration of this technology into Integrated Pest Management (IPM) programs offers a promising approach for environmentally sustainable crop protection. Nevertheless, challenges related to large-scale dsRNA production, regulatory frameworks, biosafety, cost-effectiveness, and farmer adoption remain. Future research should prioritize field validation under Nigerian agroecological conditions, optimization of nanocarrier systems, and policy development to facilitate commercialization. Overall, nano-enabled SIGS represents a promising biotechnology with significant potential to enhance sustainable crop protection, agricultural productivity, and long-term food security in Nigeria.

KEYWORDS

Nano-encapsulation, Spray-Induced Gene Silencing, RNA interference, plant disease and pests' management, Nigeria, biofungicides, sustainable agriculture

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INTRODUCTION

Agricultural productivity in Nigeria is significantly constrained by both established and emerging crop pests and plant diseases, posing serious threats to food security and economic stability. Cereals, legumes, and vegetables, staple and cash crops in the country, are particularly vulnerable to a diverse range of insect pests, nematodes, bacteria, viruses and pathogenic fungi[1-4]. The fall armyworm (*Spodoptera frugiperda*), stem borers, and plant-parasitic nematodes are among the major pests that com promise yield quantity and quality[5,6]. Emerging pests, often exacerbated by climate change and shifting agro-ecological conditions, are increasingly reported in regions previously considered pest-free, complicating management strategies[2,7]. Moreover, farmers' perceptions of pest and plant disease severity often vary across landscapes, influenced by socio-economic and agronomic factors, which further affects timely intervention[7,8].

Historically, plant disease and pest control in Nigeria has relied heavily on chemical fungicides and pesticides. While effective in the short term, these approaches are increasingly limited by several factors. Continuous exposure to sublethal doses has led to the development of plant disease and pest resistance, reducing long-term efficacy[9]. Chemical fungicides and pesticides also present environmental and health hazards, including contamination of soil and water, negative impacts on non-target organisms, and potential risks to human health[10]. Furthermore, conventional plant disease and pest management strategies often fail to address emerging plant diseases, require repeated applications, and can be cost-prohibitive for smallholder farmers, who constitute the majority of agricultural producers in Nigeria[2,3]. These limitations highlight the urgent need for alternative, sustainable plant disease management solutions that are both environmentally safe and cost-effective.

The RNA Interference (RNAi) is a natural cellular mechanism that regulates gene expression through sequence-specific degradation of target RNA molecules. Its application in agriculture allows for the targeted suppression of virulence genes critical for plant disease survival, growth, or pathogenicity, offering a highly specific alternative to broad-spectrum chemical fungicides and pesticides[11,12]. Spray-Induced Gene Silencing (SIGS) extends RNAi technology by applying Double-Stranded RNA (dsRNA) externally onto plants, with pathogens and pests uptake, triggering gene silencing and inhibiting plant disease and pest development[13,14]. The SIGS is particularly attractive because it does not require genetic modification of the host plant, reduces off-target effects, and can be integrated with existing plant disease and pest management systems[15,16]. Recent studies demonstrate its potential against fungal pathogens, insect pests, and nematodes, underscoring SIGS as a versatile and eco-friendly plant disease and pest control strategy[17-19].

Despite its promise, SIGS faces several challenges, including dsRNA instability under field conditions, rapid degradation by environmental nucleases, and limited uptake by target pathogen and pests[20,21]. Nanotechnology offers a transformative solution by encapsulating dsRNA within engineered nanoparticles, which protect the molecules from degradation, enhance their stability, and facilitate efficient uptake by pathogens and pests[22-24]. Nanocarrier-mediated SIGS has been shown to prolong the protective effect of dsRNA, improve gene silencing efficiency, and potentially allow for lower application doses, reducing costs and environmental impact[25-27]. In the context of Nigeria, where emerging plant diseases and pest pressures and limited access to advanced agricultural technologies persist, nano-embedded SIGS represents a sustainable, precise, and scalable alternative for plant disease management.

This review aims to synthesize current knowledge on the application of nano-enabled spray-induced gene silencing (SIGS) for the management of established and emerging plant diseases in Nigeria. Specifically, it examines the challenges posed by plant diseases and the limitations of conventional management strategies, provides an overview of RNA interference (RNAi) and SIGS technologies, highlights the role of nanotechnology in improving the stability, delivery, and efficacy of SIGS, and identifies current research gaps, potential applications, and future prospects for integrating nano-enabled SIGS into sustainable plant disease management programs in Nigeria.

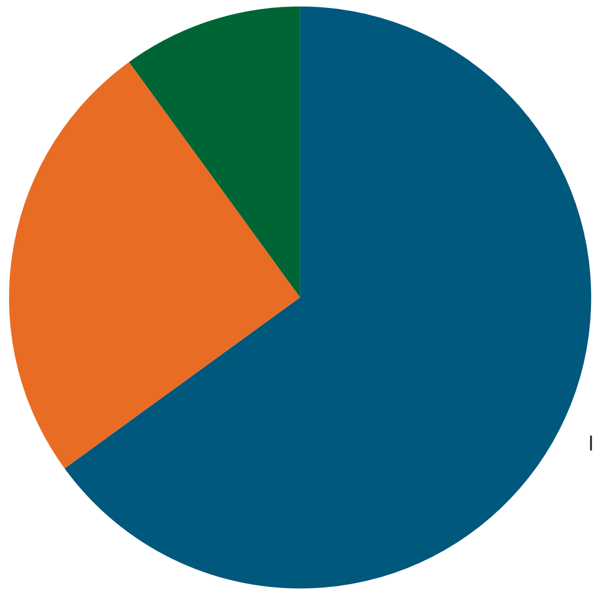

Fig. 1: Percentage of insect vs fungal vs nematode pests in Nigerian staple/cash crops

Crop pests and plant diseases in Nigeria: Crop production in Nigeria is severely affected by a wide spectrum of pests, including insect pests, plant-parasitic nematodes, and fungal pathogens, which collectively contribute to substantial yield losses and reduced crop quality as represented in Fig. 1. Staple crops such as maize, rice, sorghum, millet, cassava, and vegetables are particularly vulnerable, given their widespread cultivation across diverse agro-ecological zones[2-4]. Insect pests such as stem borers, rice leaf folders, aphids, whiteflies, and the invasive fall armyworm (*Spodoptera frugiperda*) remain among the most destructive, with maize production being especially impacted[3,6]. These pests not only cause direct feeding damage but also act as vectors for plant pathogens, further exacerbating crop losses.

Plant-parasitic nematodes represent another major but often under diagnosed threat to Nigerian agriculture. Species belonging to *Meloidogyne*, *Pratylenchus*, and *Heterodera* genera have been reported in cereals and other food crops, leading to impaired nutrient uptake, stunted growth, and yield decline[1,5]. Accurate identification of these nematodes remains challenging due to morphological similarities, highlighting the need for integrated diagnostic approaches combining molecular, biochemical, and morphometric tools[1].

Fungal pathogens such as *Botrytis cinerea*, *Rhizoctonia solani*, and powdery mildew-causing fungi further contribute to crop disease burdens, particularly in humid regions of Nigeria[10]. These pathogens are responsible for post-harvest losses and reduced market value, especially in vegetables and cash crops. Collectively, the burden of pests and pathogens in Nigeria mirrors global trends, where pests account for a substantial proportion of yield losses in major food crops[10].

Emerging pest threats in Nigeria are increasingly linked to climate change, globalization, and changes in agricultural practices. Rising temperatures, altered rainfall patterns, and increased frequency of extreme weather events have expanded the geographical range and survival capacity of several pests, including fall armyworm and cereal insect pests[2,6]. International trade and cross-border movement of agricultural commodities further facilitate the introduction of invasive species, complicating pest surveillance and control. These dynamics underscore the need for adaptable, sustainable, and precision-based pest management strategies suited to Nigeria's evolving agro-ecological landscape[2,7].

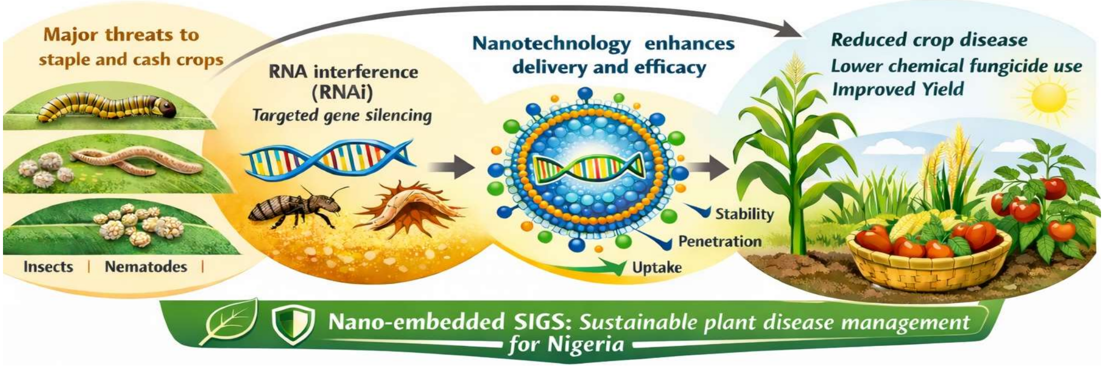

Fig. 2: Illustration of Nano-Embedded Spray-Induced Gene Silencing (SIGS) highlighting the integration of dsRNA design, nanocarrier delivery, and plant disease-specific gene silencing to enhance crop protection

Overview of RNAi technology: The RNA Interference (RNAi) is a conserved, sequence-specific gene regulation mechanism that operates through the degradation or translational inhibition of messenger RNA (mRNA). The process is initiated by Double-Stranded RNA (dsRNA), which is cleaved by the enzyme Dicer into Small Interfering RNAs (siRNAs). These siRNAs are incorporated into the RNA-induced silencing complex (RISC), guiding the complex to complementary target mRNA sequences, resulting in gene silencing[11,20].

The specificity of RNAi has been harnessed for pest control by targeting genes essential for pest survival, development, reproduction, or pathogenicity. In agricultural applications, RNAi enables selective suppression of pest genes without affecting non-target organisms, making it an attractive alternative to conventional chemical pesticides[12,15]. The RNAi-based pest control strategies have been demonstrated against a wide range of targets, including insect pests, nematodes, and phytopathogenic fungi[17,21].

Compared to traditional pesticides, RNAi-based approaches offer several advantages. These include high target specificity, reduced environmental persistence, minimal toxicity to beneficial organisms, and compatibility with integrated pest management (IPM) systems[11,13]. Importantly, RNAi strategies can be rapidly adapted to emerging pests by redesigning dsRNA sequences, providing flexibility in response to evolving pest populations and resistance development[12]. These attributes position RNAi as a promising next-generation technology for sustainable crop protection.

Spray-induced gene silencing (SIGS): Spray-Induced Gene Silencing (SIGS) is an RNAi-based pest management strategy that involves the exogenous application of dsRNA onto plant surfaces as represented pictorially in Fig. 2. Following application, dsRNA is absorbed by the plant or directly taken up by target pests and pathogens, triggering RNAi-mediated silencing of essential genes[13,14]. Unlike transgenic approaches, SIGS does not require genetic modification of the host plant, making it more socially acceptable and potentially easier to regulate and deploy[15].

The SIGS differs fundamentally from Host-Induced Gene Silencing (HIGS). In HIGS, plants are genetically engineered to express dsRNA targeting pest or pathogen genes, whereas SIGS relies on topical delivery of dsRNA formulations[11,13]. While HIGS offers long-term protection, it faces regulatory, biosafety, and public acceptance challenges. SIGS, in contrast, provides a non-transgenic, flexible, and scalable alternative that can be integrated into existing agricultural practices[14,15].

Globally, SIGS has shown considerable promise across multiple pest systems. Successful applications include the control of fungal pathogens such as powdery mildew and *Botrytis cinerea*, as well as insect pests and plant diseases affecting cereals and horticultural crops[16,18,19]. Step-by-step frameworks for SIGS implementation against fungal pathogens have further demonstrated its reproducibility and adaptability

Fig. 3: Flow diagram depicting the sequential stages of nano-embedded SIGS

Table 1: Nanocarrier types for dsRNA delivery

Nanocarrier type	Material	Benefits (Stability, Uptake)	Target pests/Pathogens
BioClay nanosheets	Layered Double Hydroxide (LDH), Magnesium/Aluminum	High UV protection, "BioClay" provides slow release (up to 30 days), non-toxic and biocompatible	PMMO Virus, Cucumber Mosaic Virus, *Fusarium oxysporum*
Polymer nanoparticles	Chitosan (natural polysaccharide)	Biocompatible, cationic nature binds dsRNA strongly, enhances midgut penetration in insects	*Spodoptera frugiperda*, *Helicoverpa armigera*, *Plutella xylostella*
Lipid-Based (Liposomes)	Phospholipids, DOTAP, DODMA	Mimics natural cell membranes, excellent cellular uptake via endocytosis, protects against nucleases	*Botrytis cinerea* (Fungus) *Spodoptera frugiperda*
Carbon-Based	Carbon Dots (CDs), Carbon Nanotubes (CNTs)	High surface-to-volume ratio, enables systemic translocation through plant vascular systems	*Nicotiana benthamiana* (model), Grapevine leafroll virus, Aphids
Dendrimers	Star Polycations (SPc)	Controllable size/charge, condenses dsRNA into stable complexes, significantly improves cuticle penetration	*Chilo suppressalis*, *Myzus persicae*, *Bemisia tabaci*
Mesoporous silica	Silica (SiO_2)	High loading capacity within pores, thermal stability, allows for "tunable" release rates	*Fusarium oxysporum*, Tobacco Mosaic Virus (TMV)
Peptide-Based	Cell-Penetrating Peptides (CPPs)	Rapidly crosses both plant cell walls and insect gut membranes, high specificity	*Aphis glycines*, Root-knot nematodes (*Meloidogyne* spp.)
Metal nanoparticles	Gold (Au) nanoparticles	Easily functionalized surface, allows for high-precision delivery and bio-imaging/traceability	*Spodoptera frugiperda*, *Tribolium castaneum*

Wytinck *et al.*[20], Yang *et al.*[29], Shafiqul Islam *et al.*[23]

under experimental and semi-field conditions[17]. These global case studies provide compelling evidence that SIGS can serve as a versatile and environmentally sustainable tool for pest management, with strong potential for adaptation to Nigerian cropping systems.

Role of nanotechnology in SIGS

Nano-carriers for dsRNA delivery: One of the primary challenges limiting the field application of Spray-Induced Gene Silencing (SIGS) is the rapid degradation of Double-Stranded RNA (dsRNA) in environmental conditions. Exposure to ultraviolet radiation, nucleases, and fluctuating pH reduces the stability and persistence of dsRNA, thereby limiting its efficacy[20,21]. Nanotechnology offers a transformative solution by encapsulating dsRNA within various nano-carriers, which protect the molecule and enhance its delivery to target pests or pathogens[22,24].

Several types of nano-carriers have been developed for dsRNA delivery. Lipid-based nanoparticles provide biocompatibility, membrane fusion capabilities, and enhanced cellular uptake[22,23]. Polymeric nanoparticles, including chitosan and polyethyleneimine-based carriers, offer controlled release and protection against enzymatic degradation[25,28]. Clay nanosheets, such as layered double hydroxides, have been shown to adsorb dsRNA effectively, prolonging its stability on plant surfaces and facilitating uptake by pests[26,29].

Additionally, artificial nanovesicles and engineered nanotransporters have been explored for targeted delivery, improving gene silencing efficiency and reducing required application doses[27,30]. Collectively, these nano-carriers serve as protective vehicles that enhance dsRNA stability, prevent premature degradation, and enable efficient uptake by pests and pathogens (Table 1 and Fig. 3).

Mechanisms enhancing efficacy: Nano-carrier systems improve SIGS efficacy through multiple mechanisms. First, they enhance penetration into plant surfaces, overcoming the barrier posed by the cuticle and facilitating the transfer of dsRNA to pest feeding sites or pathogen infection sites[18,22]. Second, nano-carriers allow for controlled and sustained release of dsRNA, ensuring prolonged gene silencing effects and reducing the frequency of application[25,31]. Third, nano-formulations improve target specificity, as dsRNA sequences can be precisely designed against essential pest genes, reducing off-target effects on non-target organisms and beneficial insects[21,26].

Recent studies highlight the synergistic effects of combining nanocarriers with dsRNA. For instance, lipid-based nano-formulations enhanced RNA uptake by fungal pathogens and insect pests, leading to more consistent and robust suppression of target genes[22,32]. Similarly, polymeric and clay-based carriers were shown to stabilize dsRNA in challenging environmental conditions while maintaining high silencing efficiency against both fungal and bacterial plant pathogens[18,29]. These findings underscore the critical role of nanotechnology in addressing the inherent limitations of conventional SIGS applications.

Safety and environmental considerations: While nano-embedded SIGS represents a promising strategy, its environmental safety and regulatory aspects must be carefully considered. Many nanomaterials used as carriers, such as lipids, chitosan, and certain clays, are biodegradable and minimally toxic, reducing the risk of accumulation in soil or water systems[22,24]. Nevertheless, potential impacts on non-target organisms, including beneficial insects, soil microbiota, and aquatic organisms, require further investigation[21,33]. Some studies have reported transient effects on phyllosphere microbiota in cereal crops following SIGS application, highlighting the need for careful assessment of ecological interactions[33].

From a regulatory perspective, nano-enabled SIGS offers advantages over traditional chemical pesticides due to its biodegradability and target specificity, potentially facilitating faster adoption and approval in countries like Nigeria[12,23]. However, national frameworks for the evaluation of nano-formulated biopesticides are still developing, emphasizing the need for comprehensive biosafety guidelines, standardized risk assessments, and monitoring of field applications[22,34]. Addressing these safety and regulatory considerations will be critical for the successful deployment of nano-embedded SIGS in sustainable agriculture.

Applications of nano-embedded SIGS in pest management

Controlling established pests: Nigeria's agriculture faces significant challenges from well-established pests such as fall armyworm (*Spodoptera frugiperda*), stem borers, and various nematodes, which threaten staple crops including maize, rice, and sorghum[1,3,6]. Conventional chemical pesticides have been widely applied to manage these pests, however, their effectiveness is declining due to pesticide resistance, environmental contamination, and non-target toxicity[2,9].

Nano-embedded SIGS presents a promising alternative. Studies in Africa and other regions have demonstrated that dsRNA-based sprays, when delivered with nanocarriers, effectively reduce pest populations. For instance, nanocarrier-mediated dsRNA targeting essential genes of lepidopteran pests has shown significant mortality and suppressed feeding behavior[22,34]. In fungal pathogens such as *Botrytis cinerea*, SIGS delivered via lipid and polymeric nanoparticles significantly reduced infection severity, highlighting the versatility of this approach for multiple pest types[18,19].

Moreover, nano-embedded SIGS has been shown to prolong dsRNA stability, enhancing its persistence on leaf surfaces and improving uptake by target pests, which can reduce the frequency of applications and mitigate the challenges of rapid environmental degradation[31,32]. These characteristics are especially critical for smallholder farmers in Nigeria, where consistent access to chemical pesticides may be limited[7,8].

Combating emerging pests: Climate change, global trade, and agro-ecological shifts have facilitated the emergence of new pest threats in Nigeria, including invasive insects, viral vectors, and pathogenic fungi[2,6]. Early intervention is essential to prevent these pests from compromising food security. Nano-embedded SIGS allows for rapid adaptation, as dsRNA sequences can be designed specifically against newly identified pest genes, offering a highly targeted and selective management tool[12,22].

For example, emerging nematode species that threaten cereal crops can potentially be controlled via dsRNA sprays delivered through polymeric or clay-based nanocarriers, reducing nematode reproduction and feeding[1,5]. Similarly, SIGS approaches may suppress emerging viral or bacterial pathogens by silencing genes essential for replication or virulence[21,26]. Integrating these strategies proactively can safeguard crop yields and support national food security goals in the face of unpredictable pest invasions.

Integration with existing pest management strategies: Nano-embedded SIGS is highly compatible with Integrated Pest Management (IPM) approaches. By providing a targeted, environmentally friendly alternative to chemical pesticides, SIGS can complement biological control agents, crop rotation, and cultural practices[13,22]. This integration can reduce chemical pesticide use, lowering environmental contamination and minimizing risks to non-target organisms[9,33].

Field-level studies have highlighted that SIGS can be combined with conventional pest management tools, offering additive or synergistic effects. For instance, foliar sprays of dsRNA in combination with pheromone traps or biocontrol agents can enhance pest suppression while maintaining ecological balance[17,20]. Such strategies are particularly relevant for Nigerian smallholder farmers, where cost-effective and sustainable pest management is critical[7,8].

By integrating nano-embedded SIGS into IPM frameworks, it is possible to enhance pest specificity, reduce resistance development, and improve overall crop productivity, paving the way for a sustainable agricultural future in Nigeria and across sub-Saharan Africa.

CHALLENGES AND LIMITATIONS

Technical limitations: While nano-embedded SIGS has demonstrated significant potential in pest management, several technical challenges impede its large-scale adoption in Nigeria. A primary limitation is production cost, as synthesizing high-quality dsRNA and incorporating it into nanocarriers remains expensive compared to conventional pesticides[22,34]. The cost burden is compounded by the need for specialized equipment and trained personnel for nanocarrier formulation and dsRNA handling, which may not be widely accessible to smallholder farmers[25].

Another technical hurdle is production scalability. Current laboratory-scale methods for dsRNA synthesis and nanoformulation are not easily translatable to field-scale applications. For example, ensuring consistent dsRNA loading into nanoparticles while maintaining stability under environmental conditions such as UV exposure, rain, and temperature fluctuations remains challenging[29,31]. Additionally, certain pests or pathogens exhibit variable uptake efficiency of dsRNA, necessitating tailored delivery strategies for each target organism, which complicates generalized formulations[20,21].

Regulatory and biosafety hurdles in Nigeria: Regulatory frameworks for RNAi-based technologies, particularly nano-embedded SIGS, are still underdeveloped in Nigeria[35]. Unlike traditional chemical pesticides, RNAi-based biopesticides straddle the domains of biotechnology and chemical regulation, creating ambiguities in approval processes[12,22]. The biosafety concerns include the potential off-target effects of dsRNA on non-target organisms, environmental persistence of nanocarriers, and unintended gene silencing in beneficial insects or soil microbes[24,33].

Addressing these issues requires robust risk assessment protocols, post-application monitoring, and clear regulatory guidance, which are currently limited in Nigeria. The absence of standardized national policies on RNAi-based nanobiopesticides slows adoption and investor confidence, despite promising research outcomes[22,23].

Knowledge gaps and farmer adoption issues: Even when technical and regulatory challenges are resolved, farmer adoption of nano-embedded SIGS presents another significant limitation. Many smallholder farmers in Nigeria rely on traditional chemical pesticides and may have limited awareness of RNAi technologies or nanocarrier applications[7,8]. Knowledge gaps extend to understanding proper application rates, timing, and safety practices, which are critical for effective pest control and minimizing environmental impacts[3,4].

Additionally, cultural and socio-economic factors influence adoption. Farmers may perceive RNAi-based sprays as complex or unreliable compared to conventional products, particularly when immediate visible pest mortality is not evident[2,7]. Extension services and training programs are therefore essential to bridge these gaps and ensure that the benefits of SIGS technology are translated into practical, field-level pest management solutions.

FUTURE PERSPECTIVES AND RECOMMENDATIONS

Research directions: To fully realize the potential of nano-embedded SIGS in Nigerian agriculture, focused research is necessary on several fronts. First, there is a need to optimize dsRNA formulations for stability under local environmental conditions, including high temperatures, intense sunlight, and heavy rainfall[29,31]. Research should also explore novel nanocarriers, such as biodegradable polymers and clay nanosheets, that enhance dsRNA uptake and controlled release while minimizing environmental persistence[24,27].

Second, studies should investigate species-specific RNAi targets for prevalent and emerging pests in Nigeria, including fall armyworm, stem borers, and nematodes, ensuring high efficacy while reducing off-target effects[1,5,6]. Cross-disciplinary research integrating molecular biology, nanotechnology, and agronomy is essential to design field-applicable SIGS solutions that are both effective and sustainable[22,25].

POLICY AND REGULATORY RECOMMENDATIONS

For successful adoption, the Nigerian government should develop clear regulatory frameworks for RNAi-based nanobiopesticides. These should include standardized risk assessment protocols, guidelines for biosafety testing, and monitoring strategies for off-target impacts on beneficial organisms and soil health[12,22]. Incentives such as subsidies, tax breaks, or grants could support local production of dsRNA formulations and encourage private-sector investment.

Moreover, policymakers should promote collaboration between regulatory bodies, research institutions, and agricultural extension services to bridge the gap between laboratory research and field application, ensuring that SIGS technologies meet both safety and efficacy standards[22,23].

Farmer education and capacity building: A critical component of future adoption is farmer education and training. Extension programs should focus on raising awareness about the benefits, application methods, and safety of nano-embedded SIGS, particularly for smallholder farmers, who form the majority of Nigeria's agricultural workforce[7,8].

Training initiatives could include demonstration trials, mobile application-based advisory systems, and participatory workshops, which allow farmers to observe the effectiveness of SIGS firsthand. Emphasizing cost-effectiveness, reduced chemical pesticide use, and environmental sustainability will improve acceptance and encourage widespread adoption[2-4].

Integrating SIGS into sustainable pest management: Nano-embedded SIGS should be promoted as a component of integrated pest management (IPM) rather than a standalone solution. By combining SIGS with biological control agents, crop rotation, resistant varieties, and judicious chemical use, farmers can achieve robust pest control with minimal environmental impact[13,15,22].

Future research should focus on long-term monitoring to assess the cumulative effects of SIGS on pest populations, beneficial insects, and soil microbiota, ensuring that these strategies contribute to resilient and sustainable agricultural systems[18,33].

Nano-embedded Spray-Induced Gene Silencing (SIGS) represents a cutting-edge, sustainable approach to pest management in agriculture. By leveraging nanotechnology to enhance the stability, uptake, and targeted delivery of dsRNA, this strategy offers precise control of both established and emerging pests, while minimizing the negative environmental and health impacts associated with conventional chemical pesticides[22,29,31].

For Nigerian agriculture, which faces significant challenges from pests such as fall armyworm, stem borers, and plant-parasitic nematodes, nano-embedded SIGS has the potential to improve crop productivity, enhance food security, and reduce dependence on synthetic agrochemicals[1,5,6]. Its integration into Integrated Pest Management frameworks can ensure long-term, sustainable pest control while preserving beneficial organisms and the broader ecosystem[15,33].

To fully realize this potential, there is a need for continued research on locally relevant dsRNA targets, optimized nanocarrier formulations, and field validation, alongside the establishment of robust regulatory frameworks and biosafety guidelines[12,22,25]. Equally important is farmer education and capacity building to facilitate responsible adoption and effective application of these technologies[7,8,35].

CONCLUSION

Agricultural productivity in Nigeria is constrained by both established and emerging crop pests and plant diseases, posing serious threats to food security. Insect pests, plant-parasitic nematodes, bacteria, viruses and fungal pathogens have been implicated with substantial yield losses and reduced crop quality. In Nigeria, pest and diseases associated with plants have been controlled by the use of chemical fungicides and pesticides which has increasingly become less effective due to exposure to sublethal doses resulting in a wide range of plant disease and pest resistance, reducing long-term efficacy. However, nano-embedded SIGS offers a transformative pathway toward sustainable, efficient, and environmentally friendly pest management in Nigeria, with potential to the improvement in food security and food quality. With coordinated efforts across research, policy, and extension services, this technology can play a pivotal role in securing the future of Nigerian agricultural sector.

In conclusion, nano-embedded SIGS offers a transformative pathway toward sustainable, efficient, and environmentally responsible pest management in Nigeria. With coordinated efforts across research, policy, and extension services, this technology can play a pivotal role in securing the future of Nigerian agriculture.

SIGNIFICANCE STATEMENT

This review highlights nano-enabled Spray-Induced Gene Silencing (SIGS) as an innovative and environmentally sustainable alternative to conventional pesticides for managing plant diseases and pests in Nigeria. By integrating nanotechnology with RNA interference, this approach enhances the stability, delivery, and efficacy of dsRNA while reducing environmental contamination and pesticide resistance. The review provides a foundation for future research, policy development, and commercialization of nano-enabled SIGS to strengthen integrated pest management, improve crop productivity, and enhance food security in Nigeria.

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