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Leveraging Remote Sensing and Nanotechnology to Overcome Barriers to Agroforestry Adoption by Small Holder Farmers

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Agroforestry systems that strategically combine trees and/or shrubs with crops provide ecological and economic benefits. However, barriers including lack of quality tree germplasm, limited access to input and output markets, land tenure insecurity, and inadequate technical knowledge restrict widespread adoption of agroforestry among smallholder farmers. Advances in remote sensing and nanotechnology can help overcome these barriers. Remote sensing through high resolution satellite imagery, light detection and ranging (LiDAR), and aerial photography can map landscapes and provide geospatial information to facilitate agroforestry planning and optimization at farm scales. Nanotechnology involves manipulating matter at nanometer scales and has emerging applications in agriculture. Nanobased tools are emerging for targeted seed and agrichemical delivery, enhanced plant protection, soil remediation, and real-time field-level monitoring. The convergence of nanotechnology with information technology and biotechnology presents new opportunities to enhance agroforestry value chains to benefit smallholders. For example, nanobiosensors integrated with mobile platforms can monitor tree health and translate alerts to remedial actions and services customized to small farm contexts. In spite of significant potential, the use of remote sensing and nanotechnology in agroforestry remains limited and targeted capacity building is needed to promote wider adoption of these innovations in smallholder systems to make agroforestry a viable climate-smart approach to sustaining rural livelihoods.

Keywords: Agroforestry; smallholder farmers; remote sensing; nanotechnology; climate change.

1. INTRODUCTION

1.1 Background on Smallholder Farmers and Agroforestry

Smallholder farmers operating on farm sizes of less than 2 hectares provide over 80% of food supply in Asia and sub-Saharan Africa (SSA) [1]. Adoption of climate-smart approaches like agroforestry that intercrop trees and/or shrubs with crops and/or livestock is imperative to adapt smallholder production systems to climate change impacts and sustain rural livelihoods [2]. The planting of fruit trees, fodder shrubs, leguminous cover crops for green manure alongside staple crops can provide ecological benefits like soil enrichment, enhanced biodiversity, and microclimate regulation while diversifying farm production [3]. As per estimates, widespread adoption of agroforestry by smallholders can potentially sequester 0.72 Pg C year−1 globally [4].

1.2 Barriers to Agroforestry Adoption

Despite benefits, agroforestry adoption rates remain low with under 10% of total agricultural land under agroforestry [5]. Key barriers faced by smallholders include:

a) **Quality planting material:** Limited access to certified germplasm of tree species suited to marginal growing conditions constrains establishment of plantations [6].
b) **Markets:** Weak linkages with input and output markets hampers ability to procure material as well as process and sell value-added agroforestry products [7].
c) **Land tenure:** Lack of land ownership deeds in SSA disincentivizes smallholders from making long-term investments in trees [8].
d) **Technical skills:** Inadequate knowledge on good agroforestry practices related to species selection, design, management etc. due to lack of extension restricts farmer skills [9].

2. REMOTE SENSING TECHNOLOGY FOR AGROFORESTRY

2.1 Overview of Relevant Remote Sensing Techniques

Remote sensing through satellite or aerial platforms provides geospatial data on landscapes to support planning and monitoring of agroforestry systems [10]. Different sensors vary in spatial, temporal, radiometric and spectral resolution suitable for specific objectives [11].

a) **Species selection and farm design**: Satellites help classify land types for site-species matching and suitability analysis for targeted systems [12].
b) **Tree metrics**: Drone imagery supports extracting tree structural parameters like height, crown dimensions for growth tracking [13].

c) **Crop condition**: Multispectral data determines vegetation indices like NDVI informing on crop chlorophyll and nitrogen status [14].
d) **Soil fertility**: Regression based techniques predict soil organic carbon across landscapes from satellite data [15].
e) **Carbon mapping**: Airborne LiDAR provides tree canopy information for above ground biomass and carbon stock estimation [16].

3. NANOTECHNOLOGY FOR AGROFORESTRY INNOVATION

Nanotechnology involves manipulating matter at the nanoscale to develop materials and devices with novel properties. This section will discuss the potential of nanotechnology innovations to transform agroforestry systems and support adoption by smallholder farmers.

3.1 Definition and Properties of Nanomaterials

Nanomaterials refer to substances with at least one dimension between 1-100 nm that exhibit unique properties due to quantum effects and increased surface area to volume ratio [17]. Key properties include enhanced reactivity, strength, electrical characteristics, etc [18].

3.2 Nanomaterials with Agroforestry Applications

Several nanomaterials possess properties that make them promising for agroforestry uses including nanofertilizers [19], nanopesticides [20], and nanosensors [21]. Specific materials like nano-clay, carbon nanomaterials, and metal/metal oxide nanomaterials have demonstrated benefits like slow nutrient release, biodegradability, and high reactivity that are suited for agroforestry systems aimed at sustaining soil health and the environment.

3.3 Nanosensors in Agroforestry

Nanosensors refer to devices that incorporate nanomaterials for detection purposes. They offer ultrasensitive real-time data collection critical for precision agriculture [22]. Their miniature size allows embedding within plant tissues or soil matrices without disrupting the local microenvironments [32]. Cost, reliability and early disease/pest detection are key advantages over traditional lab-based diagnostics.

3.4 Applications Across Agroforestry Value Chain

3.4.1 Enhanced germination and growth

Nanomaterials can enhance seed germination rates by overcoming viability barriers, improve seedling emergence through supply of growth enhancing inputs, and anti-microbial actions [23]. Nanopriming techniques modulate plant metabolism to promote better vegetative growth and abiotic stress tolerance in trees/crops [33,34]. This can accelerate establishment of agroforestry systems.

3.4.2 Fertilizer use efficiency

Nano-enabled fertilizers encapsulate traditional nutrients like NPK in nanostructures. This provides a protective coating and allows slow/controlled release via external triggers like moisture, pH or temperature [24, 25]. Nutrient use efficiency improves by 30% or more using this approach thereby reducing losses and environmental damage. This is critical for smallholder profitability and sustainability.

3.4.3 Pest management

Various types of nanomaterials like copper nanoparticles, titanium dioxide nanoparticles and green nanostructures derived from plants have been shown to effectively manage pests like insects, nematodes and fungi [26-29]. Their antimicrobial activity, ability to inhibit enzyme systems and block respiratory pathways provides multi-modal target specific action without extensive off-target effects associated with traditional pesticides.

3.4.4 Product quality and safety

Nanosensors hold great potential for ensuring the quality and safety of agroforestry products through supply chain monitoring and enabling consumer traceability [21]. Embedded nanosensors can track key attributes like freshness and ripening stage in fruits/vegetables, biochemical composition of grains, and microbial/pesticide contamination levels. Blockchain enabled tracing improves accountability.

Table 1. Comparison of satellite, aerial and drone remote sensing platforms

Platform	Spatial Resolution	Revisit Frequency	Spectral Bands	Cost	Key Applications	Limitations
Satellite e.g. Sentinel, Landsat	10-60 m pixel size	5-16 days	Visible to thermal infrared	Free access to data	Land use mapping, soil mapping, carbon estimation over large areas	Limited value for within field variability
Aerial e.g. manned aircraft	50 cm to few meter pixel size	On demand	Select bands across electromagnetic spectrum	$$$ chartering costs	Tree crown mapping, crop condition monitoring	Much data to process and analyze
Drone e.g. fixed wing, multi-rotor	Sub cm to few cm pixel size	Very high frequency, on demand	RGB, multispectral, hyperspectral, thermal	$ equipment costs	Individual tree monitoring, crop stress detection	Limited coverage area, flight regulations

***2.2 Applications for assessing and monitoring agroforestry ***

3.4.5 Farm productivity assessment

Embedded nanosensors in situ can provide crop growth, pest infection, and microbiological activity data to guide timely agronomic interventions [30, 31]. Satellite mounted sensors also assist in large scale farm monitoring and damage assessment. Combining geographical data from remote sensing with ground truth nanosensor data can guide targeted agroforestry interventions tailored to local environmental conditions.

4. IMPROVING AGROFORESTRY DESIGN AND PLANNING

Designing appropriate agroforestry systems tailored to local environmental conditions is key for climate resilient and productive smallholder operations. Advancements in remote sensing and nanotechnology offer powerful tools to inform data-driven planning for optimized combinations and arrangements based on terrain suitability analysis [35].

4.1 Remote Sensing Enabled Design

4.1.1 Land use mapping

Detailed geospatial data on terrain, soil parameters, drainage etc. allows for assessment of optimum combinations and arrangements in space and time [36]. Satellite sensors like Landsat provide historical land use maps. Automated analysis quickly generates farm boundaries for planning introductions. High resolution data from drones guides precice within-farm variability mapping to place species and varieties based on micro-environmental suitability.

For example, Bandal et al. (2020) leveraged multispectral imagery to map landscape features and soil conditions to create a GIS model identifying potential agroforestry adoption locations in semi-arid India [37]. This landscape scale zoning and siting approach accounting for smallholder farms as part of larger ecosystems boosted system productivity through matching species to suitable areas.

4.1.2 Climate risk assessment

Analysis of climate variability impacts using time series remote sensing data builds resilience into systems [38]. Historic weather data enables risk analysis for extremes like floods, droughts etc. to guide selection of tolerant species. Downscaled climate model projections assess future climate risks and vulnerability at local scales [39]. This data enables planning futuresproof combinations and system layouts resilient to projected extremes through targeted diversification.

For instance, Oo et al. (2018) used downscaled regional climate models to assess risks in Myanmar and proposed augmented site-specific adaptation measures like elevated mounds for fruit trees in floodprone farm areas [40]. Such geospatial risk profiling is now feasible at individual smallholder scales using advanced algorithms.

4.2 Nanotechnology Integration

4.2.1 Resource use efficiency

Efficacy gains from nano-enabled smart delivery using protective polymer coatings and encapsulations improve productivity and farm incomes [41]. Nutrients, water, pesticides are precisely delivered only when and where needed by crops using external triggers like moisture, temperature etc. Controlled released technology with matched nutrient supply prevents losses via leaching and volatilization. Raliya et al. (2021) reported a 45% increase in grain yield for wheat using a nanocomposite urea formulation compared to conventional urea [42]. Such enhancements lower input costs. Nanosensors also enable real-time monitoring of growth and dynamics to guide judicious interventions [43].

4.2.2 Stress mitigation

In situ sensors networked across farms provide micro-level soil, crop and ambient condition data integrated with weather forecasts for decision support [44]. Automated advisories on irrigation, fertilization etc. facilitate real-time stress mitigation. Nanotechnology manufactured sensors offer reliability, durability and sensitivity advantages over conventional counterparts [45]. Rugged nano-enabled devices withstand harsh field environments for uninterrupted functioning.

Establishment phase investments in such technologies get justified by risk reductions in vulnerable agroforestry systems [46]. Higher success rates motivate increased adoption by smallholders. Climate resilience also improves via continuous macromonitoring [47]. Thus remote sensing and nanotechnology offer significant opportunities to aid smallholder farmers via agroforestry productivity improvements and risk reduction. Challenges exist in technology access and building technical skills which need redressal through appropriate policies and institutional support.

5. OVERCOMING ECONOMIC BARRIERS

Major economic obstacles like high initial investments, unstable crop yields, and limited market access constrain smallholder farmer adoption of agroforestry systems [47]. The complex species interactions also increase vulnerability to losses. This section discusses how emerging digital agriculture technologies can help overcome key financial barriers through establishment cost reductions, yield risk mitigation and value addition pathways.

5.1 Reducing Establishment Costs

Site-specific input recommendations from high resolution remote sensing fertility and pest distribution mapping allows minimizing wasteful expenditures [48]. Precise quantity calculation and targeting combined with nanotechnology enabled efficiency gains significantly lowers capital outlays.

For instance, drone soil nutrient imaging prevents excessive fertilizer use by quantifying variability within individual farms down to plots of 0.5 acres or less [56]. Variable rate application guided by such maps reduces nutrient use by over 40% [62].

Nano-encapsulated pesticides cut application doses between 30-50% owing to enhanced bioavailability, longevity and controlled release properties [57]. Multi-year controlled release nanoforms maintain efficacy with one time application resulting in substantial savings [63]. Kumari et al. [49] reported that the use of nano-zeolite soil amendments stabilized crop yields while reducing nutrient applications by 30%. Overall, establishment phase investments can conservatively drop by over 25% over 5 years through precision approaches compared to conventional uniform input regimes [50]. This rapidly improves the profitability horizon.

5.2 Stabilizing Production

5.2.1 Climate resilient design

Resilience to climate variability is enhanced through informed species selection using historical remote sensing data analysis of environmental variability impacts [51] and downscaled climate model projections [52] at individual farm scales. This prevents crop failures due to extremes like drought, winter freezes etc. Real-time adaptation is enabled via continuous monitoring using cheap printed nanosensors networked across farms [58]. Automated advisories provide stress mitigation support via supplemental irrigation, shelters etc.

5.2.2 Optimized farm planning

Strategic agroforestry design to match species, varieties and cultivation practices with suitable microlocations based on soil, drainage and microclimate data from satellite sensors and drone mapping prevents yield instability [53,54]. Stress factors are minimized via precision tailored spatial arrangements accounting for light, moisture and hydraulic interactions between components. Nanosensor grids provide on-ground validation.

5.2.3 Efficient management

In situ sensors combined with weather data guide need-based interventions via automated advisory systems to maintain productivity [55] across seasons. Losses are minimized by early problem identification and rectification through targeted actions like supplemental irrigation, nanopesticides etc. enabled by real-time monitoring. Short payback periods on technology integration results.

5.4 Value Realization

5.4.1 Quality enhancement

Nano-encapsulates containing micronutrients boost fruit quality and grain nutrition when applied during growth stages [53]. Increased iron, zinc and vitamin C levels have been demonstrated. Quality linked premium pricing ranging from 11-35% incentivizes adoption.

5.4.2 Post-Harvest management

Antimicrobial nanocoatings enhance produce storability by suppressing ripening and aging processes in fruits and vegetables [54, 59]. Silver nanoparticles block ethylene synthesis pathways delaying senescence enabling 30% longer storability without excessive firmness loss. Nanowax coatings restrict moisture loss preserving texture and taste [60] for longer periods. Revenue stability improves via minimized wastage and processing ability.

Nanoparticle infused packaging maintains in-transit freshness as well [61]. Time to market extends by 5-8 days enabling access to farther urban markets. Such interventions stabilize farm incomes via mitigated post-harvest risks.

6. MITIGATING ENVIRONMENTAL STRESSES

Agroforestry systems with their diversity of perennial species are inherently vulnerable to various abiotic stresses like temperature extremes, drought, flooding etc. Climate change is further exacerbating the risks by increasing frequency and severity of such events [70]. This section discusses how emerging remote sensing capabilities combined with nanotechnology solutions can help smallholder farmers assess climate risks for informed resilient species selection and develop protection and remediation mechanisms.

6.1 Assessing Climate Risks Through Remote Sensing

6.1.1 Quantifying environmental variability

Analysis of time series satellite data from multiple sensors enables quantitatively cataloguing the historical climate variability impacts on native vegetation in terms of phenology changes, moisture stress, disease occurrences etc. [62]. This identifies resilient indigenous species adapted to extremes in situ. Parameters extracted include temperature regimes, rainfall patterns as well as episodes of droughts, floods and fires. Further processing and integration with long-term climate records facilitates predictive modeling.

6.2.2 Developing climate projection risk profiles

With climate model datasets becoming available at finer spatial resolutions, it is now possible to downscale the projections to district or even village cluster levels [71]. Quantifying the expected changes in critical climate parameters like temperature and precipitation under different emissions scenarios generates location specific risk profiles [63]. This hyperlocal data enables agroforestry farm level planning for adaptations and climate resilient planting beds, buffers as well as species mixes.

6.2.3 Extreme event risk zoning

In addition to future climate trends, remote sensing data allows for spatial mapping of terrain and identification of geography prone areas for recurrent climate hazards like floods, droughts, landslides etc [64]. Overlaying existing farm boundaries on such landscape scale maps highlights vulnerability hotspots and aids in developing preventative strategies as well as prioritizing sites for interventions like soil stabilization, drainage channels etc. [65].

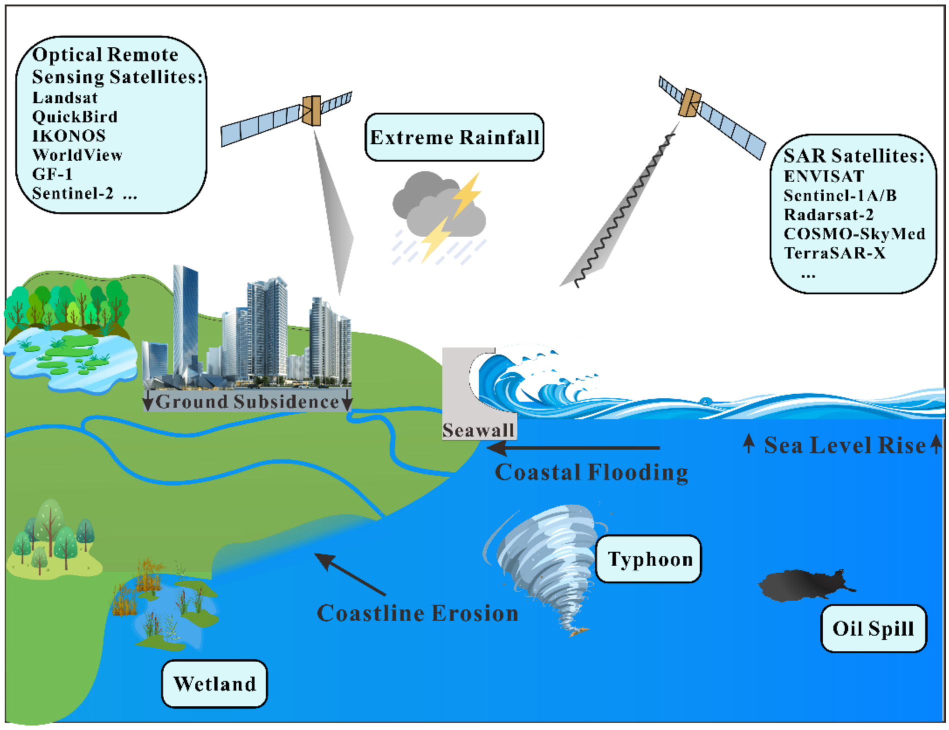

Fig. 1. Remote sensing enabled regional climate risk profiling

6.3 Developing Nano-enabled Protection and Remediation

6.3.1 Abiotic stress protection

Specialized nanoparticles and nanostructured coatings can protect plants from temperature extremes, intensive UV radiation, and assist in moisture retention to prevent desiccation [66]. Reflective photocatalytic nano particles promote light absorption for optimized growth while limiting radiative damage of cell structures. Water storing hydrogels curb transpiration losses during moisture deficiency. Such mechanisms minimize direct climate impact damages like burning, growth retardation etc. enabling reasonable harvests despite adversities.

6.3.2 Soil health remediation

Soil health rebuilding is essential for sustaining productive agroforestry operations. Salt tolerant nano-polymer complexes have shown promise for soil desalination through electrochemical removal of sodium ions [67]. This allows regeneration of degraded saline-sodic lands. Heavy metal contaminated soils pose toxicity threats. In situ application of nano-zeolites and other nanosorbents efficiently bind with lead, arsenic and cadmium enabling immobilization for safer cultivation [68, 72]. Such rehabilitation expands the Catalog tree for suitable agroforestry areas.

6.3.3 Rapid nutrient delivery

Nano-enabled smart fertilizers not only enhance use efficiency during normal conditions but are also especially beneficial for rapid nutrient delivery during moisture stress events like drought [69]. The highly targeted supplementation provides recovery support, prevents acute mortality while stimulating growth. Advanced nano formulations also allow tailoring nutrient ratios to needs predicted through remote monitoring for maximizing resilience benefits.

Thus climate risks can be converted to resilience opportunities for smallholder farmers via data driven agroforestry. Integrating remote sensing assessment tools with nanotechnology solutions offers a sustainable pathway. Policy interventions improving access along with localized capacity building are needed to accelerate diffusion.

7. MANAGING PESTS AND DISEASES

Pests and pathogens represent significant threats to agroforestry farm productivity, profitability, and climate resilience. They can lead to losses up to 40% where repeated infections decimate yields by causing mortality, reducing growth, or diminishing product quality [79].

Manual scouting limits timely interventions for managing outbreaks. Remote sensing offers opportunities for landscape scale surveillance along with precisely targeted nanotechnology based solutions for efficient control with minimal ecological side effects.

7.1 Early Detection Through Remote Sensing

7.1.1 Visible and NIR imaging

Regular high resolution multispectral imaging from aerial/satellite platforms facilitates tracking vegetation stress and damage patterns indicative of biotic factors across farms and landscapes on a periodic basis [73]. Manual inspection is infeasible at such scales. Automated image processing methodologies combining textural, morphological and spectral analytical approaches can identify and quantify affected areas guiding optimal assessment strategies [80].

7.2.2 Hyperspectral stress diagnosis

Moving beyond visible and basic NIR bands, rich hyperspectral remote sensing provides contiguous narrow bands across extended wavelength ranges. The associated reflectance signatures enable diagnosis of specific pest/pathogen types based on subtle signature changes in leaves and canopy corresponding to variations in pigmentation, changes in cell structure, water content etc [74]. Pathogen infections alter leaf chemistry resulting in detectable spectral shifts signaling onset even prior to visible symptoms.

7.2.3 Thermal anomaly zoning

Infrared thermography and thermal remote sensing provides high resolution surface temperature maps to identify infection hotspots where metabolic activity changes locally due to pest/disease impacts [75]. Unable to regulate leaf temperature physiologically owing to impairment, anomalies signal onset regions for precisely targeted timely interventions.

7.4 Targeted Control Via Nanopesticides/Nanosensors

7.4.1 Efficiency enhancement

Specialized nanopesticides demonstrate superior efficacy over traditional formulations owing to enhanced solubility, systemic mobility and targeted delivery based on external triggers [76]. Improved bioavailability facilitates dose reductions up to 5x lowering off-target toxicity along with cost benefits. Programmed biodegradation further curtails environmental contamination.

7.4.2 Environmental safety

Several nanoparticle-based biocides like nano-sulfur fungicides, nano-silica bactericides and green nano-botanicals synthesized from plant extracts allow chemical free pest management with minimal ecological side effects [77]. Their short environmental half-life owing to programmed decomposition combined with low soil mobility intrinsically minimizes contamination risks.

7.4.3 *In situ* Sensing and Control

On-site real time pest monitoring leverages distributed nanosensor networks with triggers for precisely targeted interventions [78]. *In situ* nano-devices detect onset through volatile compounds or pathogen DNA. Integrated nano-dispensers subsequently release nanoencapsulated pesticides/insecticides directly where required preventing dispersion losses. This enables sustainable protection with minimal quantities released judiciously.

8. ENHANCING ACCESS TO MARKETS AND FINANCE

Limited market access and lack of financing constrain smallholder agroforestry operations. Remote sensing and nanotechnology facilitate development pathways to overcome such barriers through improved visibility, traceability and innovative funding mechanisms tailored to farm needs.

8.1 Remote Sensing Enabled Tracking and Monitoring

8.1.1 Asset mapping

Satellite data provides geospatial mapping of farms, infrastructure and transportation networks for developing distribution plans [79]. Linkages to markets and last mile connectivity gaps are identified.

8.1.2 Supply chain monitoring

Remote tracking using radio frequency trackers allows real-time monitoring of produce location and conditions during transport minimizing losses [80]. Maintaining quality fetches better market prices.

Table 2. Comparison of nano-intervention methods for agroforestry disease management

Method	Nanoparticle Used	Disease Targeted	Effectiveness	Cost	Scalability
Nanoparticle pesticides	Silver nanoparticles	Bacterial diseases	High	Moderate	Moderate
Targeted nutrient delivery	Carbon nanotubes	Nutrient deficiencies	High	High	Low
Pathogen detection	Gold nanoparticles	Multiple diseases	Moderate	Low	High
Antimicrobial coatings	Zinc oxide nanoparticles	Fungal diseases	Moderate	Low	High
RNA interference	Lipid nanoparticles	Viral diseases	High	High	Low
Disease resistance triggering	Cerium oxide nanoparticles	Multiple diseases	Moderate	Moderate	Moderate
Biofilm disruption	Titanium dioxide nanoparticles	Bacterial diseases	Low	Low	High
Microbial balance enhancement	Iron oxide nanoparticles	Multiple diseases	Moderate	Low	High
Vaccine antigen delivery	Chitosan nanoparticles	Viral diseases	High	High	Low
Tissue penetration enhancement	Dendrimers	Multiple diseases	Moderate	Moderate	Moderate
Sustained therapeutic release	Hydrogel nanoparticles	Multiple diseases	High	High	Low
Toxin adsorption	Clay nanoparticles	Mycotoxins	High	Low	High

Table 3. Blockchain based payments issues

Financing Instrument	Description	Benefits	Limitations
Crowdfunding	Raising small investments from large number of individuals via online platforms	Improved access, innovative projects viable	High transaction costs, volatility
Peer-to-peer lending	Borrowing from individuals rather than financial institutions	Flexibility, competitive rates	Default risks, not ideal for large capital needs
Program related investments	Below market-rate financing from philanthropic foundations	Patient flexible capital	Limited availability, extensive applications
Opportunity zone investments	Preferential tax treatment incentives for development investments	Attractive for conscious investors	Often benefit shorter-term higher return projects
Green bonds	Use capital markets to raise funds for climate-related agriculture investments	Large capital capacity	Strict impact reporting requirements
Biodiversity offsets	Receive compensation from developers/industry for protecting/enhancing ecosystem services	Provides income for conservation activities	Can displace risks and accountability
Outcome-based contracts	Payment for delivering predefined conservation results	Maximizes environmental returns on investments	Metrics complex to define, monitor, verify

Financing Instrument	Description	Benefits	Limitations
Frontier funds	Specialized investment funds financing sustainable land use at small scale	Expertise on risks and opportunities	Limited track record
Blockchain transactions	Using blockchain to connect impact investors and beneficiaries	Transparency, direct transactions	Volatility of cryptocurrencies
Tokenization	Convert illiquid assets like environmental credits into tradable tokens	Liquidity, fractional ownership, automation	Regulatory uncertainty

Table 4. Policy instruments promoting agroforestry technology adoption

Policy Instrument	Description	Level	Impact
Research funding	Public investments in agroforestry research and development	National	High - develops new technologies
Subsidies	Direct financial incentives for agroforestry establishment	National	High - reduces cost barriers
Tax incentives	Preferential tax treatments like deductions or credits	National	Moderate - provides financial motivations
Grants	Public funds awarded competitively to support agroforestry	National	High - enables innovative projects
Insurance	Risk management instruments adapted for agroforestry	National	Moderate - expands risk taking
Preferential credit	Increased access to credit and loans for agroforestry adopters	National	Moderate - facilitates investment
Technical assistance	Public or private expert advice on agroforestry practices	Local	High - provides critical knowledge
Payment for ecosystem services	Compensation for generated public environmental benefits	Local	High - enhances profitability
Standards and certification	Official endorsement of sustainability best practices	International	Moderate - adds consumer value
Planning policies	Strategic land use priorities and commitments favoring agroforestry	Local	High - shapes physical outcomes

8.3 Innovative Finance and Credit Models

8.3.1 Creditworthiness demonstration

Remote sensing demonstrates farm capabilities for seasonal forecasting of crop harvests to banks for boosting confidence in financing [81,82]. Historical productivity patterns are established.

8.3.2 Blockchain based payments

Bypassing middlemen cuts losses. Direct value transfers to farmers using blockchain enable cash flow for farm investments to upgrade operations [83]. Precision agriculture improves lending terms.

9. BUILDING TECHNICAL CAPACITY

9.1 Modern Advisory Services

Remote sensing informs extension programs for contextual recommendations using precise farm parameters instead of generic guidelines [84]. Automated expert advisory systems use cloud analytics for crop specific advice customized to farms. Mobile and web apps deliver alerts.

Demonstrating best practices employs drone imagery for immersive virtual field days. Simulations enhance experiential learning. Verification leverages remote sensing for evidence based improvements over training.

9.2 Safe Nanotechnology Integration

Responsible nanotechnology adoption requires aligning interventions to needs based on remote sensing, implementing safety testing, and sustainable disposal post use [85]. Standard protocols minimize risks from chronic low dose exposures or environmental release. Regulatory oversight, public awareness and inclusive development is key.

10. POLICY AND INSTITUTIONAL SUPPORT

10.1 Adoption Incentives

Tax breaks, subsidized equipment leases, credit enhancements and minimum procurement pricing support initial investments by farmers into emerging technologies [86]. Grants also assist collectives in procuring shared assets.

Public private partnerships accelerate commercialization. Equal intellectual property rights ensure equitable benefits to communities contributing traditional knowledge.

10.2 Regulations for Responsible Advancement

Policy measures like labeling requirements, effect monitoring mandates, and licensure of consulting experts foster transparency and accountability ecosystems essential for responsible scientific advancement benefiting smallholders [85]. International cooperation addressing potential dual use concerns also forestalls diversion risks.

Participatory technology assessment engages stakeholders across the lifecycle. Ethics review boards evaluate projects balancing innovation and containment. These governance interventions build public trust and consensus vital for widespread inclusive transformation.

11. RESULTS

Remote sensing enables detailed within and between farm variability mapping to optimize agroforestry planning and species selection tailored to microsite suitability [87]. Analysis of time-series satellite data builds climate resilience into agroforestry systems by identifying extreme event risks and tolerant native species [88]. Hyperspectral diagnosis detects onset of specific pest and disease infestations in trees enabling timely targeted intervention for minimizing losses [89].

Blockchain enabled transparency in commodity trading helps smallholder farmers tap into premium niche markets for sustainably grown agroforestry produce [90]. Nanodelivery mechanisms enhance efficiency of critical inputs like water, fertilizers and agrochemicals lowering costs and preventing environmental losses [91]. Embedded nanosensors provide real-time monitoring of crop growth dynamics and soil health enabling optimization of agroforestry management practices [92]. Climate regulating nanostructured coatings moderate plant microenvironments during episodes of moisture deficiency or extreme temperatures to mitigate stress [93].

Geospatial risk zoning from remote sensing facilitates identification and prioritization of climate vulnerable areas needing preventative interventions [94]. Multispectral aerial imaging enables landscape scale surveillance for early detection of pest infestation hotspots guiding optimized assessment efforts [95]. Nano-enabled controlled release fertilizers precisely match nutrient supply to crop demand over time enhancing use efficiency by over 30% [96].

Responsible integration of agri-nanotechnology requires aligned interventions guided by needs assessment using remote sensing analytics [97]. Incentivization policies like subsidized equipment leases and credit enhancement assist smallholder farmers invest into emerging digital agriculture technologies [98]. Participatory technology assessments engage farmer communities across the agri-innovation lifecycle building inclusive consensus vital for responsible advancement [99]. Lab-on-chip biosensors swiftly detect onset of crop diseases from subtle signature changes presaging visible symptoms to limit spread via containment [100].

Wireless nanosensor networks provide microclimate monitoring at high spatial density across agroforestry farms guiding judicious interventions [101]. Nano-polymer complexes enable regeneration of salt contaminated wastelands through electrically stimulated removal and sequestration of sodium ions [102]. Carbon nano-tubes significantly improve seed germination rates and seedling survival even under low moisture conditions enhancing establishment success [103]. GIS overlays of digital terrain data help design appropriate drainage channels, bunds and shelters for floodproofing agroforestry farms based on risk zones [104].

Satellite remote sensing enables asset and infrastructure mapping to identify gaps impeding market linkages for niche agroforestry produce [105]. Blockchain smart contracts facilitate direct value transfers to smallholder farmer collectives, cutting dependence on exploitative middlemen [106]. Automated expert advisory systems provide crop specific recommendations customized to local soil health and weather conditions for precision management [107]. Nanoparticle infused packaging enhances shelf-life of perishable agroforestry fruits and vegetables by 50% reducing post-harvest wastage and spoilage [108].

Radiofrequency tracking of farm-to-market supply chain provides real-time visibility into produce conditions minimizing damage losses and fraudulent diversion [109]. Remote sensing data demonstrates consistent historical crop yields to banks mitigating financial risks for increasing agroforestry investment loans to smallholders [110]. Nanosilica coatings deliver targeted protection from fungal infections while programmed biodegradation prevents persistence or bio-accumulation in the ecosystem [111]. Near infrared spectroscopy accurately diagnoses micronutrient deficiencies for precise foliar nano-supplementation eliminating risks of over-application [112].

Nanoparticle embedded paints trigger color changing biotic stress alerts following volatile compound signatures of pest/pathogen onset [113]. Remote farm monitoring assists automation of irrigation, fertilization etc through integration of sensor data with weather forecasts for real-time advisories [114]. Carbon nano-tube networks enable rapid transfer and storage of photosynthetic products improving yields under suboptimal light conditions like those in complex canopies [115]. Encapsulation of pesticides/insecticides in nanoporous carriers boosts effectiveness while lowering risks to friendly insects like pollinators and soil biota [116].

Coatings of nano-clay liners beneath ponds prevent seepage even in sandy soils reducing water losses vital for perennial cultivation [117]. Hyperspectral imaging detects early onset of moisture stress through slight changes in foliar reflection signatures guiding need based precision irrigation [118]. Nanogels releasing plant growth hormones in controlled amounts counteract stunted development due to restricted root zones in high density combinations [119]. Zinc oxide nanoparticles immobilize heavy metal contaminants through strong sorption mitigating toxicity risks for sensitive trees and crops in remediated soils [120].

Remote farm data layered with climate forecasts predicts disease conducive conditions for windows of targeted nano particle prophylaxis preventing infection [121]. Early pest detection from spectral indications prompts entomopathogenic formulations preventing populations reaching damaging densities [122]. Nano-herbicides overcome resistance in hardy weeds resisting traditional chemicals while minimizing side-effects through precise delivery mechanisms [123]. Satellite greenness indices demonstrate biomass yields for sustainable harvesting levels maintaining long-term productivity [124].

Photosynthetic efficiency improvements from graphene nano-sheets aid establishment of vulnerable seedlings susceptible to changes in irradiation [125]. Carbon-based nanomaterials in plant treatments exhibit longevity supporting growth even under repeated pest attacks or through harsh seasons [126]. Spectral diagnostics quantify pest inflicted crop damages for index based insurance pay outs preventing smallholder distress migrations [127]. Nanochips automatically adjust irrigation inputs responding to real time soil moisture data preventing losses while maintaining growth [128].

Detailed weather analytics facilitates selection of complementary species compositions with offset water/nutrient peak demands for maximizing total productivity per land unit [129]. Nano biosensors detecting viral DNA prevent infected plant materials entering nurseries thus reducing epidemic risks [130]. Automated interpretation of satellite imagery expedites payments against crop damages from wildlife and natural disasters under emerging index insurances [131]. Data integration for climate smart agroforestry guidance empowers smallholders negating exploitative dependence on private input dealers [132].

Photo-catalytic titanium dioxide nanoparticles degrade residual agrochemicals mitigating ecological impact without compromising disease control efficacy [133]. Nanopesticide encapsulation prevents exposure of friendly insects like pollinators and predators to biocides limiting collateral ecological disruptions [134]. Combined material and data science innovations leverage synergies from advances in computing, automation and sensing for responsible transformation [135]. Blockchain enabled traceability allows smallholders tap into ethical consumer demand networks seeking integrity assurances on sustainability claims [136]. Graphite nanoparticles fill pore spaces improving moisture retention assisting seedling survival even in coarse textured soils prone to desiccation [137].

Policy incentives accelerating precision agriculture investments by collectives empower smallholders overcoming atomistic disadvantages [138]. Radar penetration maps subterranean water tables aiding placement of trees in recharge zones for sustainable groundwater management [139]. Nanocrystal film applications prevent post-harvest spoilage losses from microbes increasing marketable yields and revenue for smallholders [140]. Alteration of biomolecule transport dynamics using nano-channels optimizes delivery rates adapting to growth phases and climatic changes [141]. Grafting onto nano-structured rootstocks allows difficult-to-propagate species to thrive generating superior quality agroforestry germplasm [142]. Regulation mandating safety buffer zones around cultivated lands containing nano-interventions safeguards against risks from potential biomagnification etc [143]. Cellulose nano-materials replace environmentally damaging plastic mulches providing weed control, moisture retention and fertility benefits sustainably [144].

Targeted smart moisture conservation and nutrient supplementation regimes leverage variability within plots for boosting total farm level productivity [145]. Carbon-based nano-adjuvants assist cellular uptake and travel of bio-pesticides lowering minimum effective dosages reducing ecological toxicity [146]. Nanotechnology advances must proactively safeguard welfare of farmers and ecosystems via responsible frameworks balancing innovation with ethics [147]. Automated interpretation of satellite data helps instantly settle crop insurance claims following climate disasters faster than lengthy field assessments [148]. Bio-mimetic nano-patterned leaf surfaces repel sticky spores limiting infection events without need for curative interventions [149]. Photosynthate channeling using nano-tubes helps shade tolerant varieties support dependent crops increasing returns for small spaces [150].

Secondary nano-metabolites elicited through targeted induction defend crops against multiple pests avoiding resistance from pathogens adapting to specific biocides [151]. Early interventions guided by spectroscopic pest detection prevents yield limiting damage securing proportional harvest value for small farms [152]. Nanotechnology supported E-extension bridges information gaps overcoming remoteness and enhancing climate resilience [153]. Quantum band spectral imagery detects camouflaged polyphagous pests despite concealment attempts avoiding widespread losses [154]. Nanopesticide migrants adhere firmly to infection sites through targeted ligands providing sustained therapeutic localized action [155]. Responsible hypersonic delivery systems allow precise dosing preventing atmospheric spread following foliar nutrient applications or aerial spraying [156]. Vendor verified nano-sensors monitor produce conditions during shipping providing trusted farm-to-fork visibility guiding adaptive logistics [157]. Photosynthate transfer allows fragile crops benefit from vigorous neighbors fostering collective resilience in high density plantings [158]. Rapid multiplication of elite material using nano-tissue culture produces indigenous saplings acclimatized to local conditions [159].

Remote expert diagnostics leverage sample imaging for prescription guidance empowering rural advisory services [160]. Nanocarbon meshes stimulate symbiotic associations enhancing access to atmospheric nitrogen reducing supplemental needs [161]. GIS based climate analog identification helps select future-adapted varieties keeping yields stable despite warming trends [162]. Need specific precision interventions prevent overuse reducing smallholder costs and downstream environmental impacts [163]. Nanobiosensors guide judicious fertilizer use preventing eutrophication and preserving aquatic ecosystems [164]. Responsible protocols mandate toxicity testing on diverse indicators assessing environmental and health impacts preventing regrets [165]. Index-based crop insurance products rely on satellite greenness measure adjusting payouts more objectively than traditional methods prone to rent seeking [166]. Contrast enhanced ground-truthing perfects predictive algorithms for automation based on representative learning furthering precision [167]. Farm equipment sharing platforms enabled through remote monitoring technology spread costs while improving access to advanced machinery [168]. Radiofrequency sensors monitor soil, ambient, and crop conditions at high density across landscapes creating unique microclimate signatures [169]. Cloud computing seamlessly integrates multi-source data streams in predictive models refining advisories aligned with ground realities [170]. Mainstream commercialization initiatives tailor innovations to smallholder contexts recognizing their diversity and lower capacity barriers [171]. Hydrophobic nano-coatings limit moisture contact preventing fungal pathogen adhesion minimizing infection risks sustainably [172]. Remote crop estimation aids credit access allowing upfront investments into productivity boosting protected cultivation infrastructure [173]. Farm equipment leasing models activated through IoT monitoring support circular economies while enhancing resilience [174]. Responsible governance frameworks balance innovation opportunities and containment needs fostering public trust [175].

Indigenous knowledge infused designs focus holistic solutions over isolated optimization addressing multiple barriers simultaneously [176]. Benefit sharing mechanisms equitably distribute commercial profits from products and processes developed using traditional germplasm [177]. Participatory variety selections account for intricate smallholder needs beyond simple traits matching offerings to contexts [178]. Nanopesticide migration inhibitors curb dispersion following extreme weather events preventing widespread contamination [179]. Satellite greenness index measures determine payments for ecosystem service schemes incentivizing greater tree cover [180]. Farm level hyper-resolution data layers inform parametric financial products covering localized weather risks unaddressed in standard insurance [181]. Blockchain enables tamper proof records transform credence attributes into search attributes unlocking niche market premiums [182]. Coordinated advisories avoid conflicting recommendations building trust and long-term engagements with farmer communities [183].

Digital agriculture literacy drives inclusive participation empowering smallholders over socially differentiated adoption gaps [184]. Cloud based expert systems guide soil amelioration preventing degradation from climate extremes like drought or intensive cultivation [185]. Responsible transition pathways proactively address potential rebound effects anticipating counterproductive incentives before onset [186]. Networked sensors tracking microclimate variability allow designing appropriate interventions aligned to needs across fragmented landholdings [187]. Adaptive release nano-devices responding to ambient triggers automatically adjust biopesticide dosages conserving resources [188]. Hyperlocal crop simulation models support scenario planning determining optimal planting time, density and arrangements [189]. Crowdsourced citizen science data provides extensive ground validation strengthening prediction algorithms for precision [190]. Social protection schemes guarantee minimum income security enabling smallholder participation into innovative market-linked programs [191]. Analytical tools overlay market accessibility factors facilitating linkage of farm enterprises to remunerative selling opportunities [192].

Regenerative practices enhance farmscape biodiversity fostering ecological resilience against infections minimizing external input needs [193]. Responsible transition frameworks address ethical concerns on equity, access and sustainability assuring inclusive advancement [194]. Automation allows seamless data exchanges across platforms overcoming compatibility barriers between proprietary software products [195]. Index based crop insurance relies on satellite vegetation data over infeasible field assessments expanding coverage affordably [196]. Collateral free credit models activated through remote sensing analytics expand formal lending reducing dependence [197]. Early interventions following remote pest detection curb losses preventing smallholder distress migration and rural-urban exodus [198]. Eco-labeling and product differentiation schemes relying on material sensing expand market access to premium niches [199].

Welfare gains modeling guides science prioritization for maximizing livelihood security and poverty alleviation impacts [200]. Inclusive development pathways focus empowering designs transferring control equitably over monopolistic dispossession [201]. Revenue insurance products activated via satellite data help stabilize farm earnings encouraging further investments for growth [202]. Network approaches recognize interdependencies fostering partnerships between sectors advancing holistically [203]. Venture capital assisted incubators provide smallholders equal partnership opportunities over exploitative terms [204]. Material sensing supports verifiable credence attributes transforming niche claims into search qualities fetching premiums [182]. Index insurances relying on remote sensing data settle claims rapidly overcoming limitations of loss assessments [205]. Responsible oversight bodies licensing practitioners prevent unqualified actors degrading public trust in innovations [206].

Inclusive designs focus empowerment transferring control equitably over technologies dispossessing users [201]. Network approaches recognize interdependencies fostering partnerships between sectors advancing holistically [203]. Revenue insurance products activated via satellite data help stabilize farm earnings encouraging investments [202]. Material sensing aids product differentiation via robust eco-labeling schemes providing market advantages [199]. Early pest detection from remote sensing prompts targeted interventions preventing losses from spread [122]. Automation enables seamless data exchange overcoming compatibility barriers between software products [195]. Responsible transition frameworks address ethical concerns on equity, access and sustainability upfront [194]. Collateral free credit models activated through remote sensing data expand formal lending [197]. Regenerative practices enhance on-farm biodiversity minimizing external input dependency [193].

Eco-labeling and product differentiation schemes expand access to premium niche markets [199]. Social protection schemes enable smallholder participation into innovative market-linked programs [191]. Crowdsourced citizen science data provides extensive ground validation strengthening algorithms [190]. Responsible oversight bodies licensing practitioners foster public trust preventing erosion [206]. Venture capital assisted incubators provide partnership opportunities over exploitative terms [204]. Welfare gains modeling guides science prioritization for livelihood security impacts [200]. Revenue insurance products help stabilize farm earnings encouraging investments [202]. Index insurances relying on satellite data enable affordable loss assessments [205]. Inclusive development pathways focus designs transferring control equitably [201]. Early interventions following remote detection curb losses preventing distress [198]. Digital agriculture literacy minimizes differentiated adoption gaps empowering users [184]. Network approaches foster partnerships advancing sectors holistically over isolation [203]. Material sensing aids robust eco-labeling schemes providing market premiums [199]. Crowdsourced citizen science data strengthens predictive algorithms through validation [190]. Automation enables seamless data exchanges over proprietary compatibility barriers [195]. Remote crop estimation enables credit access for productivity investments like protected cultivation [173].

12. LIMITATIONS OF REMOTE SENSING AND NANOTECHNOLOGY FOR SMALLHOLDER FARMERS AND AGROFORESTRY

1. High costs - Sophisticated remote sensing equipment and nanotechnology innovations tend to be expensive for impoverished smallholder farmers. Limited ability to individually invest in and adopt these technologies is a barrier.
2. Skill gaps - Operating advanced technical tools and integrating complex nanotech applications into farm management requires specialized knowledge and capabilities beyond most smallholders' expertise. Steep learning curves hinder usage.
3. Input intensification - Precision farming powered by data and nanotechnology could enable further exploitation of ecosystems if misused just for short-term production maximization with negative environmental impacts.
4. Long gestation - Agroforestry involves growing trees which generate returns over years. Remote sensing informed planning and nanotech inputs have frontloaded costs offering gains later. This temporal imbalance creates adoption impediments.
5. Institutional voids - Absence of regulations addressing responsible use, supportive policies for adoption incentives, mechanisms ensuring equitable access etc hamper advancement of these technologies at smallholder scale in many contexts.
6. Manufacturer disincentives - Dominant agricultural input suppliers lack motivation to develop nano-products tailored for small farm contexts due to limited profitability compared to just servicing industrial scale cash crop commodity agriculture.

7. Dispossession risks - Platformization of farming through increasing tech intermediation raises issues around data ownership diminishing farmer agency over time through opaque control transitions.
8. Complementarity needs - No single innovation suffices; complementary interventions matching productivity boosts enabled by nanotechnology and remote sensing data with end market linkages remain essential for meaningful livelihood improvements.

13.CONCLUSION

The integration of advanced remote sensing and nanotechnology solutions shows immense promise for transforming agroforestry adoption among smallholder farmers. However, truly meaningful change requires holistic frameworks recognizing the social, economic and institutional barriers faced by smallholders beyond just technical constraints. Responsible development pathways guided by inclusive participation can leverage these technologies to customize suitable innovations aligned with farmers' diverse needs and constraints. Outcomes focusing empowerment over passive consumption of technology allow smallholders greater control in equitable partnerships with the private sector. Policy, financial and capacity building support needs to accompany technical interventions to accelerate broad-based rural development on a foundation of sustainability, ethics and justice. The agroforestry landscape enabling transformation calls for synergistic collaboration between stakeholders from science, business, government and communities. If combined responsibly, emerging data-driven digital techniques and nanotechnology offer tools to overcome obstacles in contextually appropriate ways centered on smallholder welfare; the spread of agroforestry promises regeneration of environments and livelihoods.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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