

NANOTECHNOLOGY INTERVENTIONS FOR SMALLHOLDER AND RESOURCE POOR FARMERS

CHAPTER 9

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ABSTRACT: Smallholder and resource-poor farmers form the bulk of agricultural producers in many low- and middle-income countries, yet they face significant challenges: limited access to inputs (fertilizers, quality seeds, pest control), fragile soils, variable climates, poor infrastructure, and resource constraints. Nanotechnology, appropriately adapted and scaled, offers potential interventions: nano-fertilizers and nano-pesticides for efficient use of agrochemicals; nanosensors for real-time monitoring; nanocarriers for improved delivery of bioagents; and innovations in packaging or seed coatings. However, realizing these potentials demands attention to affordability, local suitability, safety, regulatory frameworks, and participatory innovation. This chapter explores the promise and practical realities of nanotechnology for smallholder agriculture: surveys of recent applications, comparative performance, barriers, and recommendations for scaling up.

Keywords: Smallholder farmers, resource-poor agriculture, nano-fertilizers; nanopesticides, nanosensors, affordability, participatory innovation, sustainable agriculture.

INTRODUCTION

Smallholder and resource-poor farmers those with limited landholdings, capital, access to markets, and institutional support constitute the backbone of agricultural production across much of the developing world. They play a pivotal role in ensuring global food security, particularly in regions such as sub-Saharan Africa, South Asia, and parts of Latin America, where a substantial proportion of the population depends on agriculture for both livelihood and sustenance. Despite their importance, these farmers operate under severe resource constraints. Limited access to credit, extension services, and modern agricultural inputs reduces their productivity potential, while environmental degradation and climate variability further compound their vulnerability. Their production systems are characteristically risk-prone, marked by low nutrient availability, pest and disease pressures, erratic rainfall, and deteriorating soil health. These interconnected challenges undermine not only yields but also the long-term sustainability of smallholder agriculture (Mirbakhsh, 2023).

Traditional agricultural interventions have long sought to address these challenges through the dissemination of high-yielding crop varieties, synthetic fertilizers, chemical pesticides, and irrigation schemes. However, such interventions often produce modest or diminishing returns when applied under resource-poor conditions. The uniformity of these inputs does not account for site-specific soil heterogeneity or microclimatic variations that are typical of small farms. Moreover, the overuse or misuse of chemical fertilizers and pesticides has led to severe environmental consequences nutrient runoff, groundwater contamination, loss of soil biota, and reduced resilience of agroecosystems. These issues underscore the limitations of conventional input-intensive agricultural paradigms, particularly in fragile agroecological systems where sustainability and affordability are critical. As the global population continues to rise, projected to exceed nine billion by 2050, the pressure to produce more food from diminishing natural resources has intensified, prompting the need for innovative and sustainable technological solutions (Aloo *et al.*, 2021).

Climate change adds an additional layer of complexity to this already precarious situation. The increasing frequency of extreme weather events prolonged droughts, flash floods, heatwaves, and unpredictable rainfall patterns has disrupted planting cycles and reduced crop reliability. For smallholders, who lack financial buffers or access to crop insurance, a single failed season can have devastating consequences. Traditional risk management strategies, such as crop diversification or migration, are becoming increasingly inadequate in the face of accelerating climatic uncertainty. Consequently, there is an urgent imperative to develop technologies that not only enhance productivity but also build resilience into smallholder systems—technologies that are resource-efficient, environmentally benign, and adaptable to the realities of low-input farming contexts.

In this scenario, nanotechnology has emerged as a promising frontier with the potential to transform the agricultural landscape. Nanomaterials, typically within the range of 1 to 100 nanometers, possess unique physicochemical properties enhanced surface area, reactivity, solubility, and controlled release characteristics that can be harnessed for diverse agricultural applications. These include nano-fertilizers for improved nutrient delivery, nano-pesticides for targeted pest control, nano-sensors for precision monitoring of soil and plant health, and nanocoatings for crop protection and post-harvest preservation (Santos *et al.*, 2024; Gupta *et al.*, 2023). Such innovations align well with the needs of smallholder systems, where maximizing input efficiency and minimizing losses are crucial determinants of success. For instance, conventional fertilizers often suffer from low nutrient use efficiency only a fraction of the applied nitrogen or phosphorus is absorbed by plants, with the remainder lost through leaching or volatilization. Nano-fertilizers, due to their higher surface reactivity and controlled release properties, can significantly reduce such losses while maintaining optimal nutrient availability over longer periods. Similarly, nano-encapsulated pesticides can enhance the bioavailability of active ingredients and reduce environmental contamination by ensuring targeted and sustained release.

The potential benefits of nanotechnology for smallholder and resource-poor farmers extend beyond efficiency gains. They also encompass economic and environmental advantages. Reduced input wastage translates directly into lower costs, while improved productivity can strengthen household food security and income stability. Environmentally, the precision and lower dosage requirements of nano-agrochemicals can mitigate the ecological footprint of agriculture, reducing soil toxicity and protecting beneficial microorganisms. Furthermore, nanotechnology can facilitate the development of low-cost, portable diagnostic tools and biosensors that enable early detection of nutrient deficiencies, pest infestations, or water stress capabilities that could revolutionize on-farm decision-making in regions where extension services are weak or absent.

Despite this compelling potential, the practical translation of nanotechnology from laboratory research to field-scale application remains limited, particularly in low-resource settings. Most existing studies on nano-agriculture have been confined to controlled laboratory or greenhouse experiments, often focusing on high-value crops or large-scale commercial systems. There is a significant paucity of empirical data evaluating the performance, safety, and socio-economic feasibility of nanotechnological interventions under smallholder conditions. The high cost of production and limited access to nanomaterials, coupled with inadequate awareness among farmers and policymakers, further impede adoption. Regulatory frameworks governing the use of nanomaterials in agriculture are also underdeveloped in many developing countries, creating uncertainty around safety standards, environmental risks, and long-term impacts. These gaps highlight a critical research and policy challenge: how to adapt and scale nanotechnology innovations to meet the specific constraints and capacities of smallholder farmers without exacerbating existing inequalities (Yimer & Abena 2019).

Addressing these challenges requires a multidimensional approach. Research must move beyond proof-of-concept studies to focus on field-level validation under diverse agroecological contexts. Socioeconomic assessments are essential to evaluate affordability, adoption potential, and gender dimensions, as smallholder agriculture often relies heavily on women's labor and decision-making. Interdisciplinary collaborations between material scientists, agronomists, economists, and rural development experts are vital to design context-appropriate nano-based solutions. Moreover, partnerships with local institutions, farmer cooperatives, and public extension systems can facilitate participatory technology development and knowledge dissemination. Such collaborations can ensure that nanotechnology does not remain an elite science confined to academic laboratories but becomes an accessible tool for inclusive agricultural transformation.

The research gap thus lies in bridging the disconnect between technological innovation and field-level applicability. While the scientific understanding of nano-agrochemicals and nano-sensors has advanced considerably, their practical implications in smallholder systems remain poorly understood. Questions concerning long-term soil health impacts, potential bioaccumulation, and ecological safety remain unresolved. Moreover, the social and institutional dimensions of nanotechnology adoption trust, risk perception, regulatory oversight are underexplored. Without addressing these aspects, even the most promising innovations risk stagnating at the pilot stage. Therefore, the overarching objective of contemporary research in this field should be to develop, test, and scale nanotechnological interventions that are not only scientifically robust but also economically viable, socially acceptable, and environmentally sustainable within the unique contexts of smallholder and resource-poor farmers (Kekeli *et al.*, 2025).

In light of the foregoing discussion, the central objective is to explore how nanotechnology can be harnessed to enhance productivity, resilience, and sustainability in smallholder agriculture. This entails examining the efficiency and effectiveness of nano-fertilizers, nano-pesticides, and nano-sensors in improving nutrient uptake, pest management, and stress detection; assessing their environmental and health implications; and identifying the institutional and policy frameworks necessary for safe and equitable adoption. By focusing on the intersection of innovation and inclusivity, such research seeks to generate evidence-based pathways that enable smallholders to benefit from the technological frontier rather than be marginalized by it.

Ultimately, the integration of nanotechnology into smallholder farming systems represents not merely a scientific challenge but a broader developmental opportunity. It calls for reimagining agricultural modernization in ways that prioritize the needs of the most vulnerable producers while safeguarding ecological integrity. If effectively harnessed, nanotechnology could contribute to a paradigm shift from input-intensive to knowledge-intensive agriculture where precision, efficiency, and sustainability coexist. However, realizing this potential demands sustained commitment to participatory research, ethical oversight, and policy coherence. Only through such an integrated approach can nanotechnology truly serve as a transformative force for smallholder and resource-poor farmers, enabling them to thrive in an era of growing uncertainty and environmental stress.

Recent Advances and Application Examples

Applications of nanotechnology in smallholder contexts span several domains. One area of active research is nanofertilizers designed for slow or controlled release. In Africa, systematic reviews show that nanofertilizers can improve fertilizer use efficiency by 20-50%, reducing loss through leaching and volatilization (Agro-nanotechnology in African Agriculture, 2023). For resource-poor farmers, this means lower quantities needed, lower cost overall, and less environmental damage (Yadav, Yadav & Ahmad, cited in that review) (see Table 1 for comparative data). In parallel, nanopesticides and nano-formulations of botanicals or microbial agents have been studied. For example, the “State of nanopesticides application in smallholder agriculture production systems” review reports that nanopesticide formulations often achieve the same pest control effect at lower dosages, with fewer spraying rounds, thereby reducing labor and exposure risks (2024) PubMed. Another domain is biofertilizers augmented by nanotechnology: recent studies show that encapsulating plant growth-promoting rhizobacteria (PGPR) or rhizobia with protective nano-coatings can improve their viability in harsh soils, enhance root colonization, and increase nutrient uptake.

Smallholders can also benefit from nanosensors and monitoring tools that provide timely information on soil moisture, nutrient status, disease or pest onset. Though cost and technical complexity are barriers, some pilot interventions for instance, remote sensing coupled with nanotech sensors in agroforestry systems, or smartphone-enabled disease detection models – show promise in improving decision making and reducing wasted inputs. Another important set of applications is seed coatings and soil amendments using nanoscale materials. These aim to protect seedlings from pathogens, help drought tolerance, or modulate soil physical properties (water retention, aeration) by adding nano clay or nanocarbon materials. While many of these are still experimental, smallholder trials report enhanced germination rates and better survival under stress.

Comparative Performance, Benefits, and Trade-offs. When comparing nanotechnology interventions versus conventional or bulk input-based practices in smallholder systems, several patterns emerge. Table 1 below summarises comparative results from multiple studies.

Table 1: Comparative Outcomes of Nanotechnology Interventions Vs Conventional Inputs in Smallholder Farming Systems.

Intervention Type	Location / Crop	Conventional Practice Outcome	Nano-Intervention Outcome	Benefits to Farmer	Concerns / Trade-offs
Nano-fertilizers (controlled-release)	Kenya, maize	Lower yield increases (~10-15%), high fertilizer costs, soil nutrient runoff	Yield increases ~25-40%, fertilizer use reduced 30-50%, lower runoff	Cost saving, environmental benefit, higher profitability	Initial cost of nano-fertilizer, access, farmers' training needed
Nanopesticides / botanical nano-formulations	India, pulses/fiber crops	Frequent spraying, pest resistance, high human exposure	Lower frequency spraying, targeted delivery, reduced exposure	Health benefits, labor savings, less loss due to pests	Potential residual effects, regulation, acceptability
Biofertilizer + nano-encapsulation	Ethiopia, legumes	Biofertilizers with poor survival, low effectiveness under stress	Improved survival, nodulation, higher yields, stable effect under stress	Enhanced soil fertility, resilience, long-term benefit	Shelf life, cold chain/logistic constraints
Nanosensors / soil-moisture / disease alert systems	Uganda / remote areas	Guesswork irrigation, reaction after disease outbreaks	Early warning, optimized irrigation, reduced losses	Water savings, risk reduction, better crop health	Cost of sensors, maintenance, connectivity issues
Seed coatings / soil amendments	Semi-arid India	Low germination under heat/drought, seedling mortality	Increased germination, seedling survival, improved drought tolerance	Reduced seed loss, better stand establishment	Material cost, scaling up, safety perceptions

From the data, key benefits include: reduced input costs (fertilizers, pesticides), enhanced yield per input unit, lower labor risk (less exposure to agrochemicals), environmental protection (less runoff, lower pollution), and better resilience to climatic stress. However, trade-offs often revolve around cost of nano-products, availability, technical know-how, access to market/infrastructure, and concerns about long-term safety.

BARRIERS, CHALLENGES AND FUTURE

Despite growing evidence of the potential benefits of nanotechnology in enhancing agricultural productivity, the actual adoption of nanotechnological interventions by smallholder and resource-poor farmers remains limited. While laboratory studies demonstrate remarkable improvements in nutrient efficiency, pest control, and stress resilience, field-level translation is constrained by a range of financial, institutional, technical, and socio-cultural barriers. These challenges collectively shape the complex landscape of technology adoption in low-resource agrarian systems and must be critically examined to develop realistic pathways for scaling.

One of the foremost constraints is financial in nature. The upfront cost of nano-enabled agricultural products such as nano-fertilizers, nano-pesticides, nanosensors, or nanocoated seeds tends to be higher than that of conventional inputs. Smallholder farmers, who typically operate with minimal capital and limited access to formal credit systems, often find these products unaffordable. In many developing regions, agricultural finance remains underdeveloped, and lending institutions consider smallholders as high-risk borrowers due to the absence of collateral or formal credit histories. The absence of targeted subsidies or bulk procurement mechanisms further exacerbates the affordability gap. While large commercial farms may benefit from economies of scale and can negotiate favorable pricing, smallholders must purchase inputs in small quantities at retail prices, which significantly increases their per-unit cost. Consequently, even when nano-inputs demonstrate superior efficiency and longer-term benefits, the immediate financial hurdle deters adoption. Without mechanisms to lower entry costs—through subsidies, microcredit, or cooperative purchasing—nanotechnology risks becoming yet another innovation that widens the technological divide in agriculture rather than bridging it.

In addition to economic constraints, profound knowledge and awareness gaps hinder adoption. Many smallholder farmers are either unfamiliar with the concept of nanotechnology or possess limited understanding of its applications and safe handling procedures. This knowledge asymmetry extends to local input dealers and extension workers, who are often the primary sources of agricultural advice in rural communities. Traditional extension systems in much of sub-Saharan Africa and South Asia are already overstretched, under-resourced, and rarely equipped to handle new technological domains like nanoscience. In the absence of accessible and context-specific information, misconceptions and mistrust can arise. Farmers may perceive nano-based inputs as risky, untested, or harmful to health and the environment, particularly when benefits are not immediately visible. Furthermore, limited demonstration trials and participatory research initiatives reduce opportunities for experiential learning, which is essential for building trust in new technologies. The lack of feedback loops between researchers, manufacturers, and end-users prevents the co-design of products that align with local knowledge systems, cropping patterns, and resource constraints (Marzouk *et al.*, 2019).

Infrastructure and supply chain limitations represent another major bottleneck. The production, distribution, and marketing of nano-enabled agricultural inputs require specialized equipment, stringent quality control, and safe handling practices. Many low-income countries lack domestic manufacturing capacity for nanomaterials, relying instead on imports from technologically advanced economies. This dependence inflates costs and reduces the availability of products suited to local agroecological conditions. In addition, weak distribution networks, poor storage facilities, and inadequate logistics undermine product quality and reliability. Some nano-formulations may require specific packaging or cold chain systems to preserve stability, but such infrastructure is scarce in rural areas. Moreover, the absence of recognized standards, labeling protocols, and certification systems for nano-agricultural products creates opportunities for counterfeit or substandard materials to enter the market. These inconsistencies erode farmer confidence and pose potential risks to human and environmental safety. Establishing robust supply chain governance and quality assurance mechanisms is therefore crucial to ensure product integrity and user trust.

Closely related to these issues are regulatory, safety, and environmental concerns. The long-term behavior and fate of nanomaterials in complex agroecosystems remain insufficiently understood. Questions persist regarding their potential accumulation in soil and water, interactions with beneficial microorganisms, and bioaccumulation within food chains. Smallholder farmers, who often work without protective gear or standardized application practices, may face occupational health risks that are not yet fully documented. Furthermore, the lack of comprehensive regulatory frameworks for nano-agricultural inputs in many developing countries creates ambiguity about safety testing, labeling, and environmental monitoring. Where regulations do exist, enforcement capacity is limited, and coordination among environmental, agricultural, and health agencies is weak. This regulatory vacuum not only exposes farmers and consumers to potential risks but also inhibits legitimate manufacturers from investing in product development, as compliance pathways are unclear. Consequently, the establishment of harmonized international standards for nano-agricultural inputs covering aspects such as toxicity testing, particle characterization, permissible exposure levels, and degradation dynamics remains an urgent priority for ensuring safe and ethical deployment (Khundi *et al.*, 2025).

A further challenge lies in the scalability and adaptability of nanotechnology to local agroecological conditions. Laboratory and pilot studies often use standardized conditions that do not reflect the heterogeneity of smallholder farming systems, where soil fertility, water availability, and management practices vary widely across short distances. Technologies that perform well under controlled conditions may fail to replicate similar outcomes in

fragmented, resource limited environments. For example, nano-fertilizers optimized for specific soil pH or crop varieties may underperform when applied to diverse local conditions. Moreover, cultural preferences, labor availability, and gender roles significantly shape agricultural decision-making and influence whether a new input is adopted. Without participatory design processes that engage farmers in the early stages of technology development, innovations may overlook these social and ecological nuances. The resulting mismatch between laboratory efficacy and field relevance contributes to poor adoption rates and disillusionment among potential users.

Addressing these intertwined barriers requires a comprehensive and participatory approach that integrates technological innovation with socioeconomic and institutional reform. A critical first step involves enhancing affordability through local production and cost reduction strategies. Encouraging domestic fabrication of nano-inputs using inexpensive, renewable, and locally available raw materials can lower costs while fostering local entrepreneurship. Simplifying synthesis processes, promoting open-source formulations, and developing small, affordable packaging tailored to smallholder purchasing power can further enhance accessibility. Public-private partnerships and targeted subsidy schemes can play a pivotal role in de-risking adoption for early users, while microfinance and cooperative purchasing models can help farmers overcome liquidity constraints.

Equally important is the involvement of farmers throughout the research and development process. Participatory research models where farmers collaborate with scientists, extension workers, and NGOs from the initial design through field trials ensure that technologies are attuned to local realities. Farmer-managed trial plots, community level demonstrations, and iterative feedback mechanisms help refine nano-products for practical field conditions. Such engagement not only improves the technical relevance of innovations but also enhances social legitimacy and trust, key determinants of adoption.

Capacity building and extension services form another critical pillar for scaling nanotechnology in agriculture. Training programs for extension agents, agrodealers, and community leaders can facilitate accurate information dissemination about nano-products, including their benefits, risks, and safe handling procedures. Innovative communication tools such as mobile applications, interactive videos, and local-language audio programs can extend outreach to farmers in remote areas and those with limited literacy. Establishing demonstration farms and farmer field schools focused on nano-based practices can further enhance learning-by-doing and peer to peer knowledge exchange.

Strengthening regulatory frameworks and safety assessment mechanisms is equally essential. Governments should develop comprehensive, science-based policies that govern the approval, labeling, monitoring, and post-market surveillance of nano-agricultural inputs. These frameworks should include mandatory environmental impact assessments, occupational safety guidelines, and protocols for testing nanoparticle toxicity, degradation, and persistence in soils and crops. International cooperation, particularly through platforms such as the FAO, UNEP, and regional agricultural research organizations, can facilitate the harmonization of standards and ensure that developing countries are not left behind in setting global norms (Babu *et al.*, 2024).

Finally, long-term monitoring, evaluation, and evidence generation are indispensable. Sustained field trials across diverse agroecological zones are necessary to establish robust evidence on yield impacts, soil health, environmental safety, and economic viability. Evaluation metrics should go beyond yield to encompass cost-benefit ratios, labor health, ecological footprint, and resilience to climate stress. Simultaneously, innovative business models and delivery mechanisms must be explored to ensure last-mile access. This could include aggregation of demand through cooperatives, community-based distribution systems, shared sensor kits, and micro-entrepreneurship initiatives for local production or servicing. Integrating digital technologies such as mobile diagnostics, remote sensing, and blockchain-based traceability could further enhance transparency, efficiency, and scalability.

To sum up, while nanotechnology holds immense promise for transforming smallholder agriculture into a more productive, resilient, and sustainable enterprise, realizing this potential demands addressing the systemic barriers that currently constrain adoption. Financial affordability, awareness, infrastructure, safety, and local adaptability are not isolated challenges but interlinked components of a broader innovation ecosystem. A holistic strategy anchored in inclusivity, affordability, and ecological stewardship is thus imperative. By aligning technological advancement with participatory governance, policy coherence, and farmer-centered design, nanotechnology can evolve from a laboratory innovation into a transformative tool for the millions of smallholders who form the foundation of global food security.

CONCLUSION

For smallholder and resource-poor farmers, nanotechnology interventions hold real promise in overcoming key constraints: inefficient input use, pest/disease losses, unpredictable climate stress, and environmental degradation. Empirical studies suggest significant gains: reduced fertilizer and pesticide usage, improved yield, less labor risk, and greater environmental benefits. Yet, adoption barriers financial, regulatory, informational, infrastructural remain substantial and must be addressed thoughtfully. Moving forward, innovation should not be just in the nanomaterials themselves, but in how they are delivered, regulated, adapted, and made accessible. Only with inclusive design, strong safety oversight, capacity building, and supportive policy can nanotechnological tools become part of the

standard toolkit of smallholder farmers rather than niche or experimental technologies. The future of food security and agricultural sustainability depends on ensuring that these advances benefit the many, not just the few.

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