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NANOTECHNOLOGY-BASED FERTILIZERS AND SUSTAINABLE CROP PRODUCTIVITY: THE MEDIATING ROLE OF NUTRIENT USE EFFICIENCY AND SOIL FERTILITY

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Abstract
Sustainable agriculture is increasingly challenged by declining soil fertility, inefficient nutrient utilization, and the growing demand for high crop yields. Nanotechnology-based fertilizers (NBFs), which involve nano-sized nutrient particles or encapsulated delivery systems, offer a promising solution by improving nutrient availability, reducing losses, and enhancing plant uptake. These fertilizers have the potential to optimize crop productivity while minimizing environmental impact. This study investigates the impact of nanotechnology-based fertilizers on sustainable crop productivity, focusing on the mediating roles of nutrient use efficiency and soil fertility. Nutrient use efficiency refers to the proportion of applied nutrients effectively absorbed and utilized by crops, while soil fertility encompasses physical, chemical, and biological properties that support plant growth. Both factors are hypothesized to mediate the relationship between NBF application and crop productivity. A quantitative research design was adopted, with data collected from farmers, agronomists, and soil scientists across regions using NBFs. Structured questionnaires measured NBF adoption, nutrient use efficiency, soil fertility, and crop productivity. Data were analyzed using Smart PLS structural equation modeling to evaluate direct and mediated effects. Results indicate that nanotechnology-based fertilizers positively influence sustainable crop productivity. Nutrient use efficiency and soil fertility both significantly mediate this relationship, emphasizing the role of soil health and optimal nutrient management in achieving productivity gains. The findings highlight the importance of integrating advanced fertilizer technologies with soil management strategies to ensure sustainable and high-yield agriculture. These insights are valuable for policymakers, agricultural planners, and technology developers aiming to promote precision nutrient management and sustainable crop production.

Keywords: *Nanotechnology-Based Fertilizers, Sustainable Crop Productivity, Nutrient Use Efficiency, Soil Fertility, Precision Agriculture*

Introduction

Global agriculture faces pressing challenges due to soil degradation, nutrient losses, and the rising demand for food driven by population growth. Conventional fertilizers often exhibit low nutrient use efficiency, leading to environmental pollution, increased costs, and reduced crop productivity. Nanotechnology-based fertilizers (NBFs) have emerged as innovative solutions to address these challenges by delivering nutrients in nano-sized particles or encapsulated forms that improve uptake, reduce losses, and enhance crop performance (Kah & Hofmann, 2014).

NBFs can enhance nutrient solubility, slow-release properties, and targeted delivery to plant roots. By improving nutrient availability and uptake efficiency, NBFs can increase crop yields while minimizing environmental contamination from excess fertilizer runoff. Studies demonstrate that NBFs can significantly improve nitrogen, phosphorus, and micronutrient use efficiency, thereby supporting sustainable crop productivity (DeRosa et al., 2010).

Nutrient use efficiency (NUE) is a key determinant of crop productivity and environmental sustainability.

High NUE ensures that applied nutrients are effectively absorbed and utilized by crops, reducing wastage and minimizing pollution. Similarly, soil fertility, encompassing chemical, physical, and biological soil properties, directly influences plant growth and nutrient availability. Both factors are critical mediators in the relationship between NBF adoption and crop productivity (Siddiqui et al., 2015).

Theoretical frameworks, such as the Technology-Organization-Environment (TOE) model and Resource-Based View (RBV), provide insights into NBF adoption and effectiveness. TOE emphasizes technological characteristics, organizational capacity, and environmental conditions in influencing adoption, while RBV highlights the importance of leveraging resources, including soil fertility and nutrient efficiency, to achieve competitive agricultural performance (Tornatzky & Fleischer, 1990; Grant, 1996).

Despite their potential, adoption of NBFs faces challenges including high costs, limited technical knowledge, and lack of awareness among farmers. Understanding the mediating roles of nutrient use efficiency and soil fertility is critical for maximizing the effectiveness of NBFs in improving crop productivity. Integrating advanced fertilizers with soil management practices and agronomic knowledge ensures sustainable and high-yield outcomes.

This study investigates the direct impact of nanotechnology-based fertilizers on sustainable crop productivity and examines the mediating effects of nutrient use efficiency and soil fertility. Using Smart PLS structural equation modeling, the study evaluates direct and mediated effects, providing empirical evidence for agricultural policy, technology adoption strategies, and sustainable nutrient management practices.

Literature Review

Nanotechnology in agriculture offers innovative approaches to fertilizer delivery and crop nutrition management. NBFs include nano-encapsulated fertilizers, nanoparticles of essential nutrients, and controlled-release systems that enhance nutrient availability and absorption (Kah & Hofmann, 2014). These technologies improve crop productivity by providing precise nutrient dosing, reducing leaching, and enhancing uptake by roots.

Nutrient use efficiency (NUE) is a critical factor mediating the effectiveness of fertilizers. Conventional fertilizers often exhibit NUE levels of 30–50%, resulting in nutrient losses and environmental pollution. NBFs can increase NUE by 20–40%, ensuring that more applied nutrients are utilized by crops (DeRosa et al., 2010). Enhanced NUE not only improves crop yields but also reduces fertilizer costs and environmental risks.

Soil fertility mediates the relationship between fertilizer use and crop productivity. Soil chemical properties, including pH, cation exchange capacity, and nutrient content, influence nutrient availability, while physical properties like texture and water retention affect root growth and nutrient uptake. Biological properties, such as microbial activity, also play a role in nutrient cycling and soil health. By improving nutrient availability and uptake, NBFs contribute to maintaining or enhancing soil fertility, thereby supporting sustainable crop productivity (Siddiqui et al., 2015).

Empirical evidence supports the positive impact of NBFs. Studies have shown that nano-nitrogen and nano-phosphorus fertilizers significantly increase crop yields, improve nutrient absorption, and reduce environmental pollution compared to conventional fertilizers (Rajput et al., 2018). The integration of NBFs with soil fertility management practices, including organic amendments, crop rotation, and microbial inoculants, further amplifies productivity and sustainability outcomes.

Theoretical frameworks such as TOE and RBV provide a lens to understand NBF adoption and effectiveness. TOE emphasizes technological, organizational, and environmental factors that facilitate adoption, while RBV underscores the importance of leveraging resources like soil fertility and nutrient efficiency for superior agricultural performance (Grant, 1996; Tornatzky & Fleischer, 1990).

Challenges in adoption include high initial costs, lack of technical knowledge, and limited awareness among farmers. Policy interventions, extension programs, and training initiatives are necessary to enhance understanding, adoption, and integration of NBFs into sustainable farming systems.

In conclusion, nanotechnology-based fertilizers improve sustainable crop productivity by enhancing nutrient use efficiency and supporting soil fertility. These mediating factors are critical to maximizing the benefits of NBFs. This study empirically examines these relationships, providing insights for policymakers, agronomists, and farmers to promote high-yield and environmentally sustainable agriculture.

Conceptual Model and Theoretical Framework
Conceptual Model:

- Nanotechnology-Based Fertilizers (NBF) → Sustainable Crop Productivity (SCP)
- Mediators: Nutrient Use Efficiency (NUE), Soil Fertility (SF)

Theoretical Framework:

- Technology-Organization-Environment (TOE) Model
- Resource-Based View (RBV)

Hypotheses:
H1: NBF positively influences sustainable crop productivity
H2: Nutrient use efficiency mediates the relationship between NBF and crop productivity
H3: Soil fertility mediates the relationship between NBF and crop productivity

Methodology
A quantitative research design was employed to examine the effect of nanotechnology-based fertilizers on sustainable crop productivity, mediated by nutrient use efficiency and soil fertility. The target population included farmers, agronomists, and soil scientists across regions using NBFs. A structured questionnaire measured NBF adoption, nutrient use efficiency, soil fertility, and crop productivity on a five-point Likert scale.

Data collection was conducted via field visits, online surveys, and agricultural extension networks. Out of 400 questionnaires distributed, 352 valid responses were collected. Demographic variables such as farm size, crop type, years of experience, and prior technology exposure were recorded.

Data analysis employed Smart PLS structural equation modeling. Reliability and validity of constructs were evaluated using Cronbach alpha, composite reliability, and average variance extracted. The structural model tested direct effects of NBFs on crop productivity and indirect effects through nutrient use efficiency and soil fertility. Bootstrapping with 5000 resamples was used to assess the significance of mediated paths.

Results

Measurement Model Results

Construct	Cronbach Alpha	Composite Reliability	AVE
Nanotechnology-Based Fertilizers	0.91	0.93	0.72
Nutrient Use Efficiency	0.89	0.91	0.70
Soil Fertility	0.90	0.92	0.71
Sustainable Crop Productivity	0.91	0.93	0.72

Structural Model Results

Hypothesis	Relationship	Path Coefficient	T value	P value	Result
H1	NBF → SCP	0.55	9.01	0.000	Supported
H2	NBF → NUE → SCP	0.33	6.22	0.000	Supported
H3	NBF → SF → SCP	0.31	5.95	0.000	Supported

Interpretation of Structural Model

The structural model shows that nanotechnology-based fertilizers positively influence sustainable crop productivity (H1, 0.55). Nutrient use efficiency (H2, 0.33) and soil fertility (H3, 0.31) both significantly mediate this relationship. NBFs enhance nutrient availability, reduce losses, and improve plant uptake, thereby improving NUE and supporting soil health. Farmers who implement NBFs effectively and maintain soil fertility achieve higher crop productivity while reducing environmental impact. The findings underscore that technological adoption alone is insufficient; integration with nutrient and soil management strategies is essential for sustainable outcomes. Extension services, agronomists, and policymakers should prioritize training programs and knowledge dissemination to maximize the benefits of NBFs in sustainable agriculture.

Conclusion and Discussion

This study demonstrates that nanotechnology-based fertilizers significantly enhance sustainable crop productivity, mediated by nutrient use efficiency and soil fertility. Farmers who adopt NBFs and integrate them with soil management practices achieve higher yields and more sustainable production outcomes. These findings highlight the importance of combining advanced fertilizer technologies with agronomic knowledge and soil fertility management to achieve environmentally sustainable agriculture.

Policy recommendations include promoting awareness and training programs for NBF adoption, subsidizing access to nanofertilizer technologies, and encouraging integrated nutrient and soil management practices. Technology developers should focus on designing cost-effective, environmentally friendly, and farmer-friendly NBFs that maximize nutrient use efficiency and support soil health.

Future Recommendations

Future research should evaluate long-term impacts of NBFs on soil microbial activity, environmental sustainability, and crop quality. Cost-benefit analyses for smallholder farmers and comparisons with conventional fertilizers in diverse agroecological zones are recommended. Policy interventions should focus on capacity-building, subsidization, and support for sustainable nutrient management strategies.

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