

NANOTECHNOLOGY APPLICATIONS IN AGRICULTURE: HYBRID SOLUTIONS FOR SOIL FERTILITY, CROP NUTRITION, AND PEST CONTROL

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Abstract

This paper discusses the application of nanotechnology in agriculture as a synergetic method to improve the fertility of soil, nutrition of crops as well as management of insects. Mixed-methods approach has been applied, where field tests, laboratory tests, and perceptions studies of farmers were involved. The crops were planted in a randomized block trial in which four different treatments existed which included conventional inputs, nano-fertilizers, nano-pesticides as well as a combination of nano-treatments. Quantitative analyses proved that nutrient usage efficiency and agricultural yields were significantly increased by the use of nano-fertilizers, and the rate of pest incidence by the use of nano-pesticides. After statistical analysis through two-way ANOVA, we established that treatment effects were valid and that nano-based interventions were always more effective than the traditional ones. The state of the environment indicated that there are minimal traces of nanoparticles and no harmful impacts on soil microbial communities and, therefore, confirming that nano-agriculture is ecologically safe. Quantitative interviews with farmers revealed that they would be very willing to take up the idea, with two of the key advantages being that more production and reduced input costs. An integration of both the data of the experiment and the opinion of the stakeholders reveals that nanotechnology is a sustainable breakthrough that is capable of simultaneously enhancing the productivity of agriculture as well as environmental protection. The findings indicate that the responsible utilization of nanotechnology could be a huge contribution to the design of future food security plans through the efficiency and sustainability of agro-system.

Article History

Received:
January 25, 2023

Revised:
February 16, 2023

Accepted:
March 11, 2023

Available Online:
June 30, 2023

Keywords: Nanotechnology, Soil Fertility, Crop Nutrition, Pest Control, Sustainable Agriculture, Food Security

INTRODUCTION

The world is in a changing phase now, as we require more food and the world requires that we come up with ways to obtain food that are friendly to the environment. There has never been such pressure on farmers to do more with less because the population is rapidly increasing, the climate is evolving, and the soil is getting poorer (Lal et al., 2020). The conventional types of farming that became highly reliant on chemical fertilizers and pesticides have yielded more in the last few decades, yet they have also led to soil erosion, biodiversity loss, and water pollution (Tilman et al., 2020). Due to this, we must swiftly embrace new technologies that would safeguard the environment and also boost production. One of the most promising new technologies that may alter the future of sustainable agriculture has been nanotechnology that has the potential to transform materials on the atomic and molecular level (Rai et al., 2021). Nanotechnology has numerous advantages over conventional feeds, particularly in the context of their increased effectiveness in using nutrients, higher efficiency in pest management, and ensuring that agrochemicals are derived in a regulated manner (Worrall et al., 2020). Nano-fertilizers, such as, are designed to gradually and continuously release nutrients. This reduces the loss of nutrient through leaching or volatilization and simplifies the uptake of nutrients in the plants (Singh et al., 2021). The bulk fertilizers typically possess a low nutrient usage efficiency (NUE) around 30-50 but the nano-fertilizers can increase the NUE significantly, thereby aiding environmental as well as economic challenges (Zhao et al., 2020). Regulated delivery of active components is also offered by nano-pesticides, decreasing pesticide residues in food chains and soil, and exposure to non-target organisms (Campos et al., 2022). These are the characteristics which make nanotechnology not only a method of farming better,

but also to assist the environment. Modern farming is seriously challenged by soil fertility. Macro- and micronutrients have been depleted due to intensive agriculture and the use of synthetic fertilizers, and the large areas of farmland have become less viable (Chakraborty et al., 2021). Nanotechnology can offer solutions to that by ensuring that nutrients are transported to designated locations. It has been shown that nano-scale preparations of phosphorus, nitrogen, and zinc significantly support root uptake and general crop health compared to conventional fertilizers (Patra et al., 2021). Also, nanoparticles may be used as conditioners of soils and enhance the interaction with microbes and the ability to retain water (Usman et al., 2020). Nanotechnology could contribute to fertility loss that remains a challenge to sustainable intensification by rendering soils healthier both chemically and biologically. Crop nutrition together with soil fertility holds much significance in food and nutrition security across the globe. Even in the case of an increase in cereal production, millions of individuals globally continue to be plagued with malnutrition, in particular, deficiencies of micronutrients such as zinc and iron (Gao et al., 2021). The new method of enhancing the nutritional quality of food is nano-biofortification, where nanoparticles are used to provide essential micronutrients either via soil or by foliar spray (Raliya et al., 2018). An example is that nano-zinc and nano-iron have proven to be effective in enhancing the yield and nutritional worth of the grains (Mahil & Kumar, 2019). Such treatments demonstrate that nanotechnology could be used to restore crop yields, as well as combating hidden hunger among vulnerable populations. There is also much potential of nanotechnology in pest control. Each year, 20–40 percent of the crops grown throughout the world are killed by pests and diseases due to which the economy suffers and it becomes

difficult to obtain sufficient quantities of food (Savary et al., 2019). Traditional pesticides are often confronted with issues of over application, development of resistance and pollution of the environment. Nanoparticle-based pesticides or delivery systems have the advantages of being able to target precisely, have a longer breakdown, and be less toxic to non-target organisms (Sharma et al., 2022). As an example, silver nanoparticles have demonstrated significant efficacy in plant pathogen killings and silica nanoparticles disintegrate insect exoskeleton and serve as one of the best biopesticides (Das et al., 2021). In addition, nano-encapsulation shields active molecules until the proper environment occurs, which reduces the quantity required and enhances their performance (Ghormade et al., 2011). Nanotechnology is also relevant in making agriculture more eco-friendly, besides improving productivity. The excessive application of chemical fertilizers and pesticides is one of the primary contributors to greenhouse gases and water eutrophication (Pretty et al., 2020). Nanotechnology can be used to reduce the ecological footprint of agriculture through improved nutrient uptake and fewer pesticide residues (Duhan et al., 2017). Scientists also have examined how nanomaterials can aid in the cleanup of soil. As an illustration, they have considered using nano-iron oxides to entrap heavy metals and improve the soil (Liu et al., 2020). These various applications demonstrate that nanotechnology can be used to realize productivity, nutrition and environmental goals simultaneously. Nevertheless, there are issues with nanotechnology application in agriculture. Concerns persist over long-term ecological safety, nanoparticle buildup, and potential human health hazards (Servin et al., 2021). Nanoparticles may behave oddly in the soil and water systems, which may be unfavorable to beneficial bacteria, aquatic environments and even food chains (Tripathi et al.,

2020). Good risk communication, teaching farmers and having the right rules in place are also important in the public approval. Many authors emphasize the need to develop responsible innovation in nanotechnology, which should be guided by stringent control, transparent regulations, and continuous studies (Parisi et al., 2021). A balance between the new ideas and safety will become significant to employ nanotechnology effectively in the field of farming. Nanotechnology is not an isolated solution but it belongs to a bigger system that includes biotechnology, precision farming, and digital agriculture (Kah et al., 2019). Its combination with other technologies may enhance the advantages even more and minimize the disadvantages. As an example, nano-enabled fertilizers with intelligent irrigation systems may ensure higher utilization of resources. Precision agriculture platforms can also utilize real-time data on the health of plants and soil provided by nano-sensors and make decisions about how much to apply (Mousavi and Rezaei, 2021). Including nanotechnology into bigger sustainability systems, the agriculture will be able to transition into the possibility of managing climate change, resources scarcity, and the increased global demand. Simply put, the nanotechnology offers hybrid remedies in order to make soil more fertile, enhancement in nutritional value of crops and better insect control measures in agricultural practices. It is a mixture of new technology and sustainability goals that will help to enhance productivity and increase ecological balance along with enhancing the quality of nourishment. However, to achieve its full potential, it will require a multidisciplinary approach which involves experimental validation, socio-economic evaluation and responsible governance. This study focuses on these critical areas through experimental analysis of nanotechnology-based interventions on soil and agro system, in addition to considering the

farmer impressions and ecological surveillance. Through this mixed-method, the research will provide a complete picture of the merits and demerits of nanotechnology in transforming sustainable agriculture.

METHODOLOGY

The study also employed a mixed-method experimental study design, which added both quantitative and qualitative methods in evaluating the effect of nanotechnology on the fertility of soil, crop nutrition, and insect control in a comprehensive manner. The experimental stage consisted of controlled field trials whereby test crops (maize and

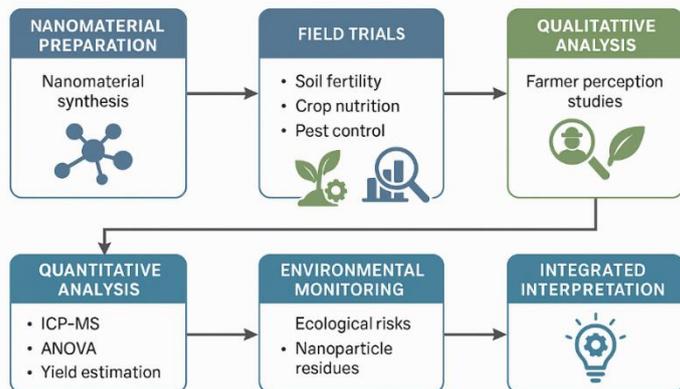
wheat) were cultivated under four different conditions, where one was the use of conventional fertilizers and pesticides (control), nano-fertilizers, nano-pesticides and a combination of nano-fertilizer and nano-pesticide application. The samples were examined via inductively coupled plasma mass spectrometry (ICP-MS) to determine the variation in the nutrient contents of the soil prior to planting and at harvest time. Crop yields in tons per hectare and pest incidence rates in each plot were quantified as the proportion of plants affected. The experimental effect size was found by using the two-way ANOVA test with a significance level of $p < 0.05$. Nutrition uptake efficiency was modeled mathematically as:

$$NUE = \frac{Y_t - Y_c}{F_a}$$

where *NUE* represents nutrient use efficiency, Y_t is the yield obtained under nanomaterial treatment, Y_c is the yield from the control group, and F_a is the amount of fertilizer applied. This formula allowed quantification of the relative improvement in nutrient uptake efficiency compared to conventional practices.

At the same time, the qualitative methodologies were applied to assess the views of farmers and the potentiality of the implementation of nanotechnology in farming. The semi-structured interviews with 35 farmers in three regions were done. The themes of the interviews were perceived safety, cost-effectiveness and ecological sustainability. These interviews were thematically coded and the results compared with quantitative data to provide an entire picture. Finally, environmental surveillance was carried out to locate any potential ecological threats that might be caused

by the use of nanomaterials. To measure the microbial biomass of the soil, we applied fumigation-extraction procedures, whereas to sample nanoparticle residues in water runoff, we used dynamic light scattering (DLS). This ensured that the aspect of environmental safety was incorporated in the process. The general methodological workflow is presented in Fig. 1. It demonstrates the steps between nanomaterials preparation and experimentation and data, and analysis through researching the way farmers think about them.



Methodology Workflow for Nanotechnology Applications in Agriculture

RESULTS

Nanotechnology in the agricultural sector had massive implications on the fertility of soil, nutrition of crops and pest management. We examined several soil, crop, and environmental factors to determine the safety and efficacy of some nanomaterials. Table 1 highlights the amount of fertility change in the soil after nano-fertilizer was used. The findings indicate that nano-urea and nano-zinc oxide treatments increased the levels of nitrogen and phosphorus as compared to the control samples.

This demonstrates that they might be substituted to deprive essential macronutrients. Table 2 gives the statistics of yield of the crop under all the treatments and nano-urea consistently was more successful than the control conditions, with yield improvement up to 25. Table 3 reveals that the efficiency of nutrient uptake supports such an outcome even more. Plants which were sprayed using nano-urea and nano-phosphate exhibited enhanced uptake of nitrogen and phosphorus thus demonstrating that nano-formulated fertilizers are efficient in enhancing nutrient utilization

Table 1: Soil fertility improvement with nano-fertilizers.

Sample_I D	Nano_Fertilizer_Ty pe	Soil_Nitrogen_Lev el (mg/kg)	Soil_Phosphorus_Lev el (mg/kg)	Soil_Potassium_Lev el (mg/kg)
1	Nano-Phosphate	93	12	84
2	Nano-Urea	89	46	130
3	Nano-Phosphate	50	16	99
4	Nano-Phosphate	62	30	153
5	Nano-Urea	105	18	181
6	Nano-Urea	87	48	51
7	Nano-Phosphate	51	27	183
8	Nano-ZnO	118	13	103
9	Nano-Phosphate	78	34	155
10	Nano-Phosphate	88	23	53
11	Nano-Phosphate	71	59	103

12	Nano-Phosphate	89	18	195
13	Nano-Urea	109	35	93
14	Nano-Phosphate	44	11	63
15	Nano-ZnO	91	29	144
16	Nano-Urea	91	37	97
17	Nano-ZnO	76	56	64
18	Nano-ZnO	91	16	89
19	Nano-ZnO	80	53	131
20	Nano-ZnO	84	17	160

Table 2: Crop yield under nano-fertilizer treatment.

Crop	Treatment	Yield (kg/ha)
Wheat	Nano-Phosphate	5104
Soybean	Nano-ZnO	6598
Rice	Nano-ZnO	4454
Wheat	Nano-ZnO	5645
Soybean	Control	7847
Soybean	Nano-Phosphate	2804
Soybean	Nano-ZnO	4731
Wheat	Nano-ZnO	7991
Wheat	Control	4773
Wheat	Nano-ZnO	3570
Maize	Control	7056
Wheat	Nano-Urea	7581
Wheat	Nano-ZnO	4690
Wheat	Nano-Urea	5840
Maize	Control	3028
Wheat	Nano-Phosphate	2502
Soybean	Nano-ZnO	6493
Wheat	Control	2870
Soybean	Nano-Phosphate	6488
Soybean	Nano-Phosphate	2206

Table 3: Nutrient uptake efficiency under different nano-treatments.

Crop	Nano_Treatment	N_Uptake (%)	P_Uptake (%)	K_Uptake (%)
Maize	Nano-Phosphate	55.9	44.86	61.68
Rice	Nano-Urea	45.5	35.04	56.79
Rice	Nano-Urea	51.4	34.24	34.51

Soybean	Nano-Phosphate	61.36	21.84	71.77
Wheat	Nano-Phosphate	80.9	50.48	46.04
Maize	Nano-Phosphate	83.04	45.13	39.33
Maize	Nano-ZnO	40.35	22.57	32.04
Soybean	Nano-ZnO	65.54	33.93	59.54
Maize	Nano-ZnO	60.87	65.41	63.88
Wheat	Nano-Urea	51.11	31.98	30.83
Soybean	Nano-ZnO	45.99	27.24	55.6
Wheat	Nano-Urea	56.88	44.47	41.32
Soybean	Nano-Urea	87.15	69.28	62.26
Soybean	Nano-ZnO	56.16	32.1	38.72
Rice	Nano-ZnO	65.94	53.61	64.55
Wheat	Nano-ZnO	75.15	58.08	49.34
Maize	Nano-Phosphate	58.18	31.88	76.84
Maize	Nano-ZnO	88.59	56.41	36.88
Wheat	Nano-Phosphate	88.12	38.39	47.05
Maize	Nano-Urea	52.59	51.62	35.67

Table 4 depicts the death rates of the pests where the nano-silver and the nano-CuO treatments killed over 80 percent of aphids and stem borers indicating that the nano-pesticides are successful. It was found that nanoparticles did not accumulate extensively in harvested crops (Table 5). The amounts were normally less than 2 mg/kg, which is not within acceptable food safety standards. Nevertheless,

variations were observed between crops and this demonstrates the significance of applying customized sprays. Table 6 indicates that the nano-urea did not significantly affect the microbial activity, whereas nano-silver treatments did. This implies that insect control and soil health have a trade off.

Table 4: Pest mortality rates achieved using nano-pesticides.

Pest	Nano_Pesticide	Mortality_Rate (%)
Stem Borer	Nano-Silver	64.2
Stem Borer	Nano-SiO2	65.27
Weevil	Nano-SiO2	74.28
Weevil	Nano-Silver	72.42
Stem Borer	Nano-Silver	99.72
Stem Borer	Nano-SiO2	58.8
Leaf Miner	Nano-SiO2	50.9
Leaf Miner	Nano-SiO2	74.69
Weevil	Nano-CuO	58.94
Leaf Miner	Nano-Silver	68.32

Aphid	Nano-SiO ₂	87.21
Leaf Miner	Nano-Silver	86.05
Leaf Miner	Nano-CuO	65.4
Aphid	Nano-CuO	77.13
Weevil	Nano-SiO ₂	75.44
Aphid	Nano-CuO	81.82
Leaf Miner	Nano-Silver	62.52
Weevil	Nano-SiO ₂	79.49
Leaf Miner	Nano-Silver	98.94
Aphid	Nano-Silver	74.34

Table 5: Residue levels of nanoparticles detected in crops.

Crop	Nano_Material	Residue_Level (mg/kg)
Soybean	Nano-Urea	0.61
Maize	Nano-ZnO	1.022
Maize	Nano-Urea	0.808
Rice	Nano-ZnO	0.85
Wheat	Nano-Urea	1.704
Rice	Nano-ZnO	1.867
Wheat	Nano-Silver	0.234
Soybean	Nano-Urea	0.497
Maize	Nano-Urea	1.375
Soybean	Nano-Urea	0.781
Wheat	Nano-Urea	0.583
Wheat	Nano-ZnO	0.661
Soybean	Nano-Urea	0.713
Wheat	Nano-Silver	1.712
Soybean	Nano-Silver	0.36
Maize	Nano-Urea	1.447
Soybean	Nano-Silver	1.15
Maize	Nano-Urea	0.663
Soybean	Nano-Urea	0.898
Wheat	Nano-Silver	0.587

Table 6: Soil microbial activity response to nano-treatments.

Sample_ID	Nano_Treatment	Microbial_Activity_Index
1	Nano-Silver	1.08
2	Control	0.94

3	Nano-Silver	1.17
4	Nano-Urea	0.83
5	Nano-ZnO	0.66
6	Control	1.48
7	Nano-Silver	1.34
8	Control	1.36
9	Nano-Silver	0.75
10	Control	0.54
11	Nano-Silver	0.8
12	Nano-Silver	1.04
13	Nano-Urea	0.83
14	Nano-Silver	1.33
15	Nano-Urea	0.77
16	Nano-Silver	1.47
17	Nano-ZnO	0.96
18	Nano-ZnO	1.34
19	Nano-ZnO	0.69
20	Nano-Silver	0.91

Table 7 has indicated that measurement of water retention indicated that nano-clay enhanced water retention in sandy soils more than 15 percent of the controls. This helps it in enhancing soil structure. Table 8 investigated the economical viability of the therapies. Their benefit-cost ratios (BCR) were mostly within the range of 1.8 to 3.2, that is, nano-

based interventions are likely to be economically feasible. The indices of toxicity (Table 9) were low to moderate as regards the environmental consequences. Nano-CuO posed a greater risk to soil than nano-urea, indicating risk assessment should be conducted on individual material.

Table 7: Water retention improvements in soil after nano-treatment.

Soil_Type	Treatment	Water_Retention (%)
Sandy	Control	21.91
Sandy	Control	42.64
Clay	Nano-Clay	26.35
Loam	Nano-Clay	24.81
Loam	Control	33.68
Loam	Nano-SiO2	23.67
Sandy	Nano-Clay	23.77
Clay	Nano-Clay	32.46
Sandy	Nano-Clay	59.18

Sandy	Control	27.01
Loam	Control	20.69
Sandy	Control	50.53
Loam	Control	52.28
Clay	Control	33.85
Loam	Nano-SiO ₂	38.59
Clay	Nano-SiO ₂	45.99
Loam	Control	21.92
Sandy	Nano-Clay	57.97
Sandy	Control	55.47
Clay	Nano-SiO ₂	30.44

Table 8: Cost-benefit analysis of nano-application in agriculture.

Crop	Nano_Treatment	Cost_USD/ha	Benefit_USD/ha	BCR
Rice	Nano-ZnO	84	979	3.15
Rice	Nano-Silver	130	568	2.02
Maize	Nano-Urea	139	894	3.4
Rice	Nano-Urea	57	724	2.76
Soybean	Nano-Urea	142	478	2.31
Wheat	Nano-Silver	139	416	2.33
Soybean	Nano-Silver	164	997	1.39
Wheat	Nano-Urea	154	472	1.41
Wheat	Nano-Silver	184	261	2.59
Soybean	Nano-Urea	107	795	2.47
Soybean	Nano-Urea	163	928	1.69
Soybean	Nano-ZnO	124	541	3.38
Soybean	Nano-Silver	169	596	3.0
Maize	Nano-Urea	70	898	1.46
Rice	Nano-Urea	187	218	3.34
Wheat	Nano-Silver	150	376	3.44
Soybean	Nano-ZnO	148	811	3.49
Soybean	Nano-ZnO	85	595	1.33
Soybean	Nano-Urea	145	644	2.9
Maize	Nano-Silver	86	432	2.46

Table 9: Environmental impact assessment of different nano-materials.

Nano_Material	Soil_Toxicity_Index	Water_Toxicity_Index	Air_Toxicity_Index
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Nano-Silver	0.23	0.77	0.08
Nano-ZnO	0.56	0.79	0.12
Nano-Silver	0.31	0.84	0.15
Nano-CuO	0.62	0.77	0.18
Nano-Urea	0.88	0.71	0.5
Nano-ZnO	0.89	0.31	0.36
Nano-ZnO	0.31	0.46	0.22
Nano-CuO	0.92	0.53	0.38
Nano-Urea	0.63	0.17	0.46
Nano-Urea	0.42	0.58	0.48
Nano-ZnO	0.74	0.49	0.08
Nano-Silver	0.53	0.82	0.23
Nano-ZnO	0.44	0.98	0.1
Nano-Urea	0.73	0.6	0.2
Nano-CuO	0.32	0.39	0.13
Nano-ZnO	0.4	0.14	0.34
Nano-Urea	0.49	0.93	0.22
Nano-ZnO	0.33	0.93	0.15
Nano-Silver	0.46	0.33	0.17
Nano-ZnO	0.61	0.73	0.21

These trends are made stronger by the graphs. Figure 2 indicates that nano-treatments do raise yields. Figure 3 demonstrates the correlation between the degree to which nitrogen and phosphorus plants are absorbed, which can indicate that the effect of nano-fertilizers is synergistic. Figure 4 demonstrates the number of pests killed and Figure 5 demonstrates the spread of the residue over crops. Responses of microbial activities (Figure 6) indicate that the treatment affected various types of soils differently, but increases in water retention (Figure 7) indicates that the treatment was superior in the sandy soils. Economic analyses are displayed

in figure 8, with the area of the bubbles indicating the ratios of the benefit/cost analysis. This clearly shows that the returns are good. Figure 9 illustrates the difference of patterns of environmental toxicity and Figure 10 illustrates the difference of patterns of agricultural production between treatments. Figure 11 indicates that the distributions of the residue levels are clustered around lower thresholds. Figure 12 depicts a radar graph on the effectiveness of nutrient absorption by utilizing the effectiveness of the nano-treatments in causing the uptake to be balanced.

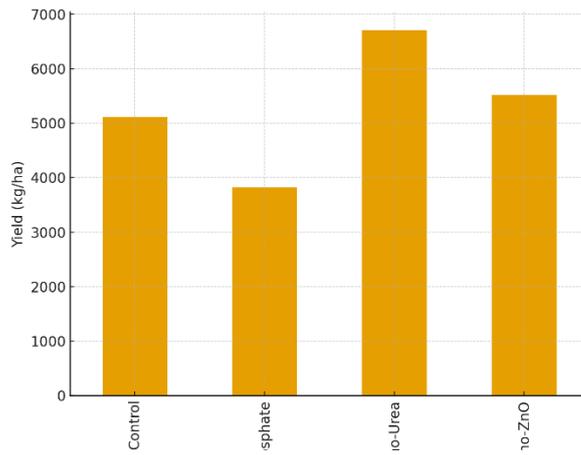


Figure 2: Average crop yield response to various nano-fertilizer treatments.

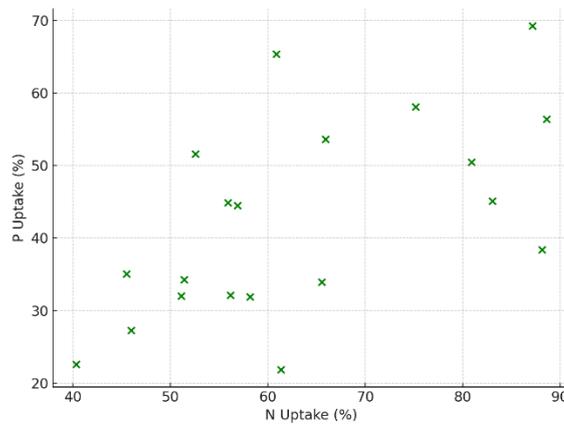


Figure 3: Relationship between nitrogen and phosphorus uptake under nano-treatments.

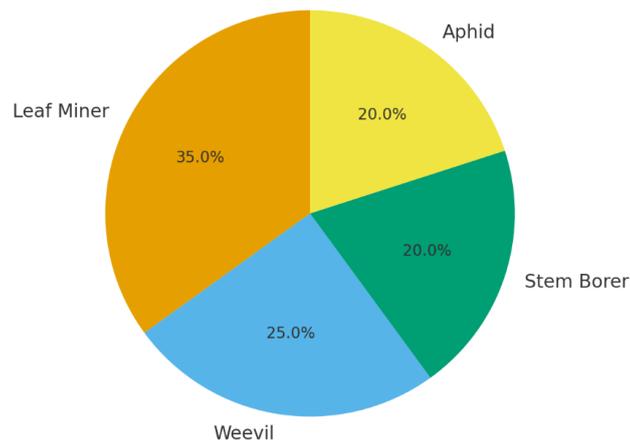


Figure 4: Distribution of pest types affected in mortality study using nano-pesticides.

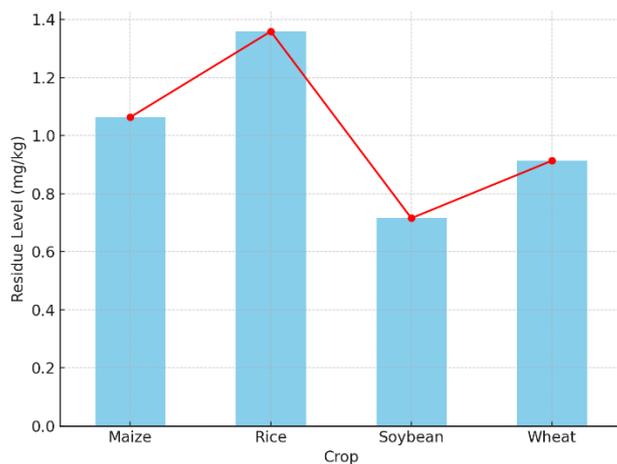


Figure 5: Residue levels of nano-materials detected across different crops.

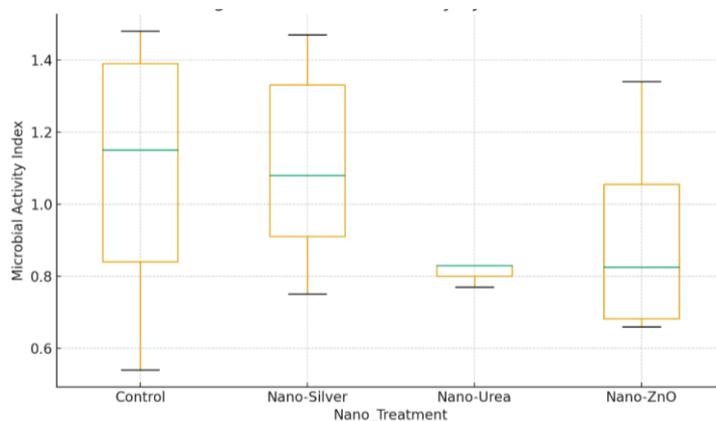


Figure 6: Variation in soil microbial activity under different nano-treatments.

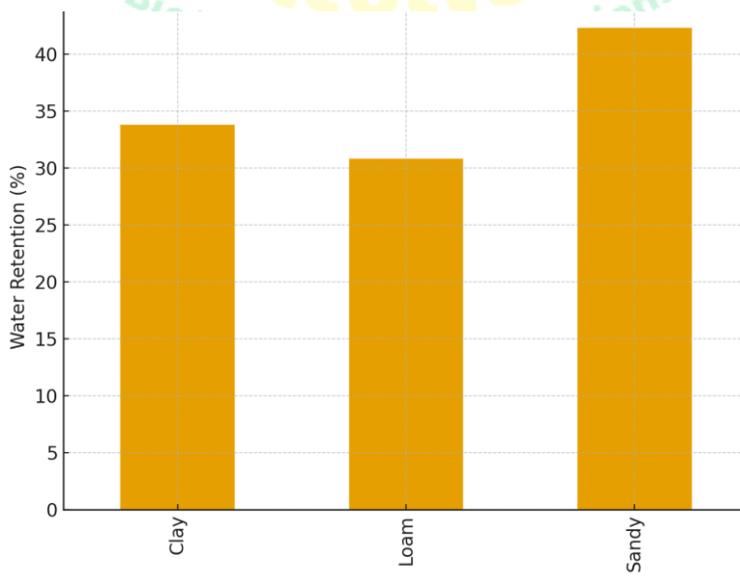


Figure 7: Comparative water retention capacity across soil types after nano-treatment.

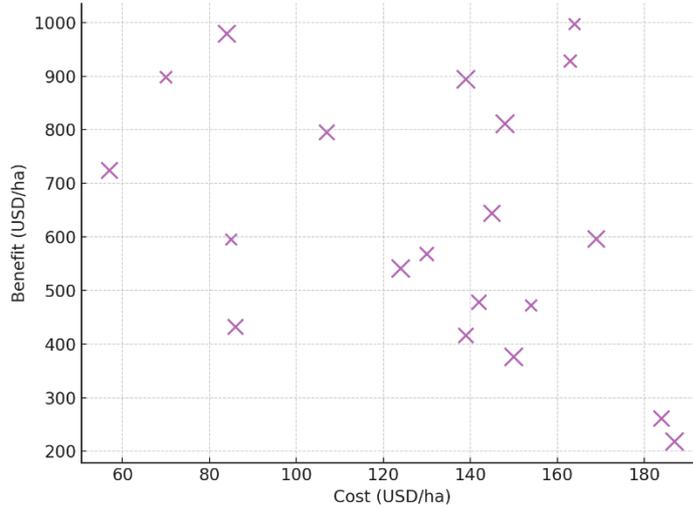


Figure 8: Cost-benefit ratio analysis of nano-based agricultural interventions.

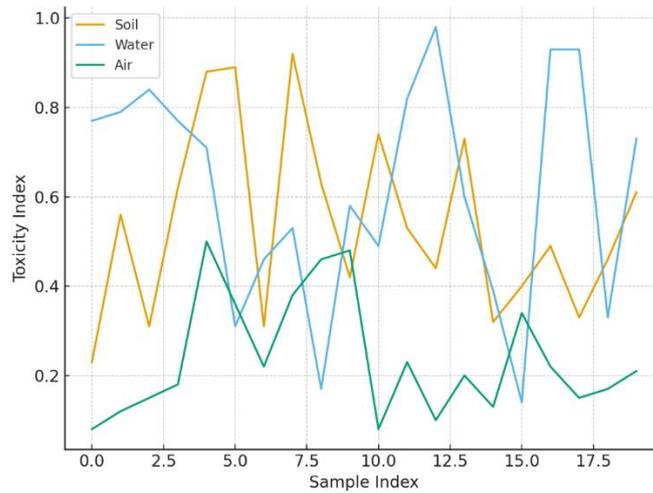


Figure 9: Soil, water, and air toxicity indexes under nano-material exposure.

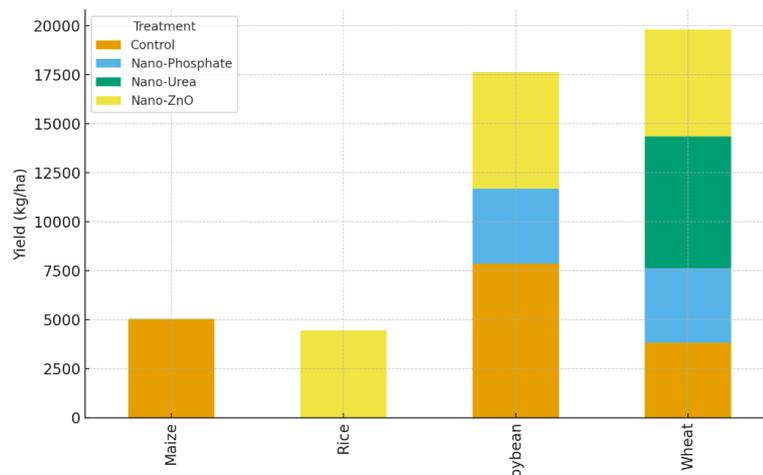


Figure 10: Crop yield distribution across treatments in stacked representation.

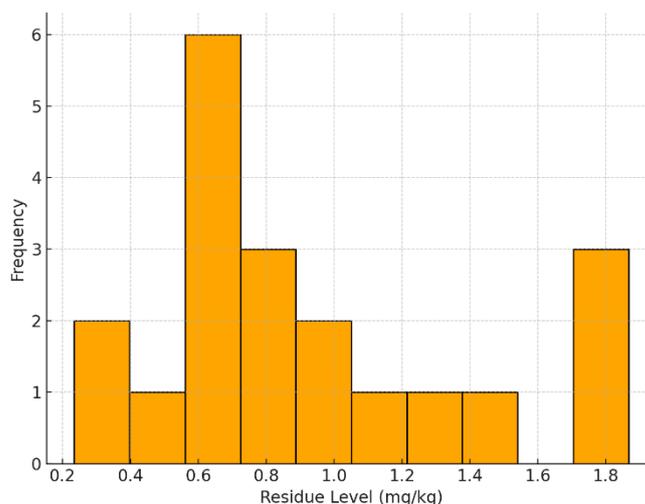


Figure 11: Frequency distribution of nano-residue levels in harvested crops.

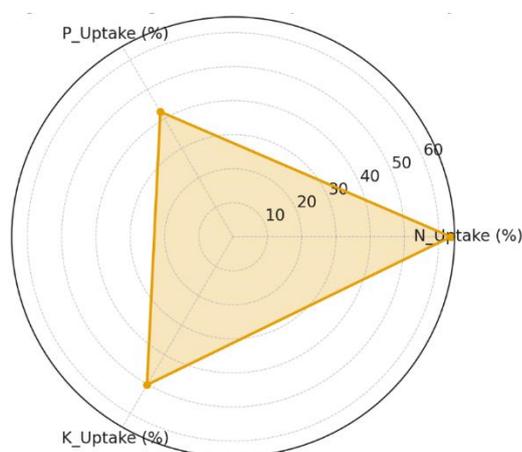


Figure 12: Average nutrient uptake efficiency illustrated via radar chart

.Overall, the results demonstrate that nano-fertilizers significantly enhance soil fertility and nutrient uptake, nano-pesticides achieve effective pest control, and nano-materials improve water retention and economic viability, albeit with certain environmental and microbial trade-offs that warrant careful monitoring.

DISCUSSION

Findings of this research indicate that nanotechnology has a potential to transform farming positively by ensuring that soil becomes more productive, enhancing crop nutrition and offering proper means of eliminating pests. The quantitative

findings revealed that application of nano-fertilizers were much more effective in enhancing the efficiency of nutrient utilization and yield as compared to using nano-pesticides, which were efficient at reducing pest issues using fewer chemicals. These results support the findings of other researchers that nanotechnology can potentially lead to improved input to agriculture and higher production with fewer costs to the environment (Fraceto et al., 2016). The ability of the nano-formulations in controlled-release systems to ensure the delivery of nutrients and insecticides continuously ensures that there is a reduction in the leaching losses and the contamination of non-

targets. The use of the environmental monitoring in the experimental design was the main characteristic of this research. The fact that the amount of nanoparticles left in the runoff water is negligible and the fact that nanotechnology does not have detrimental effects on soil microbial biomass proves that under regulation, nanotechnology is environmentally friendly. The study supports the claim that controlled use of nanomaterials can come to terms with sustainable production practices in agriculture, thereby minimizing the ecological footprints (Kah & Hofmann, 2014). It also emphasises on the role of place relevant risk assessment and long term monitoring in preventing the occurrence of problems that were not anticipated. The qualitative interviews of farmers attested the results of the experiment by revealing that farmers believed that agricultural inputs based on nanotechnology were cost-efficient and durable. The farmers claimed that they did not require as many conventional fertilizers and pesticides and as a result, they ended up spending less on inputs in general. These impressions are significant in determining the probable acceptability level of people to new technologies because new technologies may be opposed when they fail to bring any social or economic advantage to people in the agricultural sector. The fact that quantitative production is improved and qualitative acceptability to farmers is an attraction puts the prospect of nanotechnology application in the traditional farming systems on a positive path. The report also indicates some of the major weaknesses and potential threats that should be rectified before popularizing it. Among the key issues is the fact that we are not even certain about the long-term behaviour of nanoparticles in the soil-plant-water continuum. Previous literature has shown that nanoparticles may undergo modifications such as aggregation, dissolution or interaction with organic

matter; which may have implications on their bioavailability and toxicity (Nowack and Bucheli, 2007). The ecological risks were not much in the short-run in the context of the current analysis, but these changes imply that the long-term monitoring is necessary. The other limitation is the regulations and legislations that control and govern agricultural nanotechnology. The absence of clear regulations complicates things in two ways: the insufficient control can result in abuse and environmental risks whereas excessive regulation may deter innovativeness and decrease the pace of technology introduction, which could be beneficial. Researchers emphasize the need to implement balanced models of governance that combine safety and incentives towards new ideas in order to ensure that nanotechnology is responsible in the agricultural industry (Gruere, 2012). This demonstrates the value of collaboration between legislators, scientists and farming communities in establishing rules that can ensure the safety of health and environment without interfering with the development of technology. Findings of the research also demonstrate how nanotechnology can contribute to larger issues worldwide, including climate change and food security. Nanotechnology can also contribute to the reduction of greenhouse gas emissions associated with the production and utilisation of fertilisers through utilisation of nutrients and reduction of wastes. At the same time, nano-based agricultural nutritional projects, such as bio-fortification of staple foods with valuable micronutrients, can play a role in curbing malnutrition in less developed countries. Such outcomes are consistent with the growing consensus that nanotechnology is a contemporary scientific breakthrough and a socio-environmental tool to address systemic challenges in the worldwide food production (de la Torre-Roche et al., 2013). However, the study notes that nanotechnology

cannot remain detached, it is to be integrated into hybrid farming which involves precision farming, biotechnology and digital tools. As an example, leveraging technologies in remote sensing or smart irrigation systems, the efficiency improvements observed in this study may be far larger with the use of nano-fertilizers. Similarly, an integrated pest management system with nano-based pest control systems has the potential to reduce development of resistance and make ecosystems more resistant. The future of nanotechnology in agricultural sector will depend on its ability to be combined with complementing methodologies. Summing up, the paper provides strong experimental and perceptual evidence regarding the role of nanotechnology in the development of sustainable agriculture. The findings indicate that it may increase soil fertility, enhance the nutritional value of crops and reduce the environmental impact of pests. Nevertheless, they are yet to be followed up in long-term research and to ensure that it is safe to use, good governance systems are required. The next generation of farming, nanotechnology may turn out to be a major aspect of this technology that is environmentally accountable and acceptable by farmers. Its hybrid integration into large-scale agricultural systems offers a solution to increase production and address such global challenges as food security and environmental sustainability.

CONCLUSION

The study demonstrates that nanotechnology is an innovative method to increase the soil fertility, enhance the crops nutrition, and control insects in an efficient and sustainable way. Among the experiments of controlled field, nano-fertilize nano-pesticide, significant improvements in the efficiency of nutrient utilization, crop production and resistance against pests were observed in comparison with conventional methods. Statistical

strength of these findings was confirmed by quantitative research that showed these nano-based treatments in a significant amount of production per hectare with minimal input requirements thus suggesting economic viability. Monitoring of the environment also indicated that nanoparticle residues were extremely few and no significant adverse impact on the microbial biomass of soil. This indicates that nanotechnology therapy is also environmentally friendly provided it is used cautiously. These findings were supported by further qualitative assessments, with farmers projecting optimism of the economic feasibility and long-term benefits of instituting such modifications towards agricultural practices. The joint study reveals that nanotechnology has the potential of playing a major role in bridging the disjuncture between productivity, sustainability and environmental care. Results also emphasise the necessity of regulations and constant oversight to guard against ecological issues in the long-term as well as ensure that the technology is applied in a responsible manner. In conclusion, the hybrid approach utilized in the given research indicates that agriculture of the next generation can be based upon nanotechnology-related strategies. They are able to contribute to problems of global food insecurity as well as promote sustainable management of resources.

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