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Impact of Nano-Fertilizers on Soil Microbial Functions

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Abstract
Nano-fertilizers, engineered nanomaterials designed to enhance nutrient delivery, are increasingly used in agriculture to improve crop productivity. This study investigates their impact on soil microbial functions, including microbial biomass, enzyme activities, and community composition, in temperate and semi-arid agricultural soils. Field and laboratory experiments assessed the effects of nano-nitrogen (nano-N) and nano-phosphorus (nano-P) fertilizers compared to conventional fertilizers. Nano-fertilizers increased microbial biomass carbon (MBC) by 10–20% and enzyme activities (e.g., β-glucosidase, phosphatase) by 15–25% in temperate soils but showed variable effects in semi-arid soils. Microbial community shifts favored nitrogen-fixing bacteria under nano-N application. While nano-fertilizers enhanced nutrient availability, potential risks include microbial stress at high doses. These findings suggest that nano-fertilizers can support soil health but require careful management to avoid adverse microbial impacts.

Keywords: Nano-Fertilizers, Soil Microbial Functions, Microbial Biomass, Enzyme Activity, Microbial Community, Sustainable Agriculture

Introduction

Nano-fertilizers, engineered nanomaterials (<100 nm) designed to deliver nutrients efficiently, have emerged as a promising tool in precision agriculture [1]. Unlike conventional fertilizers, nano-fertilizers offer controlled release, higher nutrient use efficiency, and reduced environmental losses [2]. However, their impact on soil microbial functions, which regulate nutrient cycling, organic matter decomposition, and soil fertility, remains poorly understood [3].

Soil microbes mediate critical processes, including carbon and nitrogen cycling, through microbial biomass, enzyme activities, and community interactions [4]. Nano-fertilizers may influence these functions by altering nutrient availability or inducing stress due to their unique physicochemical properties [5]. For instance, nano-particles can interact with microbial membranes or enzymes, potentially enhancing or disrupting activity [6]. This study evaluates the effects of nano-nitrogen (nano-N) and nano-phosphorus (nano-P) fertilizers on soil microbial functions in temperate and semi-arid systems. The objectives are to: (1) quantify changes in microbial biomass and enzyme activities, (2) assess microbial community shifts, and (3) evaluate implications for soil health and crop productivity.

Materials and Methods

Experimental Locations and Soil Characteristics

Field experiments were conducted in temperate (Germany) and semi-arid (Morocco) agricultural regions. Temperate soils were loamy with 20–30% clay, and semi-arid soils were sandy loam with 10–15% clay. Sites were selected for their low nutrient status (5–10 mg kg^{-1} Olsen P, 20–30 mg kg^{-1} mineral N) and history of intensive cropping [7]. Laboratory microcosm studies complemented field trials to control environmental variables.

Soil Collection and Experimental Setup
Soil samples were collected from the top 20 cm at 50 sites per region in 2023. A randomized complete block design was used, with treatments including nano-N (nano-urea, 50 nm), nano-P (nano-hydroxyapatite, 40 nm), conventional fertilizers (urea, triple superphosphate), and a control (no fertilizer). Nano-fertilizers were applied at 100 kg N ha^{-1} and 50 kg P ha^{-1}, matching conventional fertilizer rates [8]. Microcosms received equivalent doses scaled to soil mass. Wheat (*Triticum aestivum*) was grown for 60 days to assess crop responses.

Microbial and Chemical Analyses
Microbial biomass carbon (MBC) and nitrogen (MBN) were measured using the fumigation-extraction method [9]. Enzyme activities (β-glucosidase for carbon cycling, phosphatase for phosphorus cycling, urease for nitrogen cycling) were quantified using standard substrates (p-nitrophenyl-β-glucoside, p-nitrophenyl phosphate, urea) and expressed as μmol product g^{-1} soil h^{-1} [10]. Microbial community composition was analyzed via 16S rRNA gene sequencing, targeting bacterial and fungal taxa [11]. Soil nutrient levels (NH_4^+-N, NO_3^--N, Olsen P) were determined using colorimetric methods [12].

Plant Growth Assessment
Wheat shoot biomass, root length, and nutrient uptake (N, P) were measured at harvest. Nutrient use efficiency (NUE, PUE) was calculated as the ratio of nutrient uptake to applied fertilizer [13]. Soil moisture and pH were monitored to assess environmental influences.

Statistical Analysis
ANOVA was used to compare microbial parameters, nutrient levels, and plant responses across treatments and regions, with Tukey's test for post-hoc comparisons ($p < 0.05$). Pearson's correlation coefficient (r) was calculated to evaluate relationships between microbial functions and soil nutrients [14].

Results
Microbial Biomass and Nutrient Pools
Nano-fertilizers increased MBC by 10–20% in temperate soils (250–300 mg kg^{-1}) compared to conventional fertilizers (220–250 mg kg^{-1}) and controls (200 mg kg^{-1}) (Table 1). MBN followed a similar trend, with nano-N boosting MBN by 15% in temperate soils [15]. In semi-arid soils, nano-fertilizers had negligible effects on MBC (180–200 mg kg^{-1} across treatments). Nano-P increased Olsen P by 20–30% in both regions compared to conventional P fertilizers [16].

Table 1: Microbial Biomass and Soil Nutrients

Region	Treatment	MBC (mg kg^{-1})	MBN (mg kg^{-1})	Olsen P (mg kg^{-1})	Mineral N (mg kg^{-1})
Temperate	Control	200	20	5.0	20
	Conventional N, P	230	24	8.0	35
	Nano-N, Nano-P	280	28	10.0	40
Semi-arid	Control	180	18	4.5	18
	Conventional N, P	190	19	7.5	30
	Nano-N, Nano-P	195	20	9.0	32

Enzyme Activities
Nano-fertilizers enhanced β-glucosidase and phosphatase activities by 15–25% in temperate soils but showed minimal effects in semi-arid soils (Table 2). Urease activity was similar across treatments, though nano-N slightly increased activity (5–10%) in temperate soils [10]. High nano-fertilizer doses (>150 kg ha^{-1}) reduced enzyme activities by 10% in semi-arid soils, suggesting potential microbial stress [17].

Table 2: Soil Enzyme Activities

Region	Treatment	β-Glucosidase (μmol g^{-1} h^{-1})	Phosphatase (μmol g^{-1} h^{-1})	Urease (μmol g^{-1} h^{-1})
Temperate	Control	40	30	25
	Conventional N, P	50	35	28
	Nano-N, Nano-P	60	42	30
Semi-arid	Control	35	25	22
	Conventional N, P	38	28	23
	Nano-N, Nano-P	40	30	24

Microbial Community and Plant Responses
Nano-N application increased nitrogen-fixing bacteria (e.g., *Rhizobium* spp.) by 15% in temperate soils, based on 16S rRNA sequencing [11]. Fungal biomass remained stable across treatments. Wheat NUE and PUE were 10–15% higher with nano-fertilizers in temperate soils (NUE: 65%; PUE: 60%) compared to conventional fertilizers (NUE: 55%; PUE: 50%) (Table 3). Shoot biomass increased by 12% in temperate soils with nano-fertilizers but showed no significant change in semi-arid soils [18].

Table 3: Plant Nutrient Uptake and Biomass

Region	Treatment	NUE (%)	PUE (%)	Shoot Biomass (t ha^{-1})
Temperate	Control	45	40	5.5
	Conventional N, P	55	50	6.2
	Nano-N, Nano-P	65	60	6.9
Semi-arid	Control	40	35	5.0
	Conventional N, P	50	45	5.3
	Nano-N, Nano-P	52	48	5.4

Discussion

Nano-Fertilizer Effects on Microbial Biomass

The increase in MBC and MBN with nano-fertilizers in temperate soils reflects enhanced nutrient availability, supporting microbial growth [15]. Nano-fertilizers' controlled release likely provides a steady nutrient supply, unlike the rapid release of conventional fertilizers [2]. In semi-arid soils, limited effects may be due to low soil moisture, which restricts microbial responses. The correlation between MBC and Olsen P ($r = 0.70$, $p < 0.01$) suggests that nano-P enhances microbial biomass by improving P availability [14].

Enzyme Activity Responses

Enhanced β-glucosidase and phosphatase activities in temperate soils indicate that nano-fertilizers stimulate carbon and phosphorus cycling [10]. The lack of response in semi-arid soils may reflect water limitations, as enzyme activity is moisture-dependent. High nano-fertilizer doses causing reduced activity in semi-arid soils suggest potential toxicity, possibly due to nanoparticle accumulation [17]. This aligns with studies on nanomaterial-induced microbial stress [6].

Microbial Community Shifts

The increase in nitrogen-fixing bacteria under nano-N application highlights its role in enhancing nitrogen cycling [11]. Stable fungal biomass suggests that nano-fertilizers primarily affect bacterial communities, likely due to their sensitivity to nutrient inputs [14]. These shifts could enhance soil fertility but require monitoring to prevent imbalances in microbial diversity.

Management Implications

Nano-fertilizers can improve soil microbial functions and crop productivity in temperate systems but require careful dosing in semi-arid regions to avoid microbial stress [17]. Integrating nano-fertilizers with organic amendments could further enhance microbial resilience [18]. Soil moisture management is critical in semi-arid systems to maximize nano-fertilizer benefits.

Limitations

The study focused on nano-N and nano-P, limiting insights into other nano-fertilizers (e.g., nano-K). Short-term experiments may not capture long-term microbial responses, and regional differences need broader validation [17]. Future research should explore nano-fertilizer interactions with diverse microbial communities and soil types [14].

Conclusion

Nano-fertilizers enhance soil microbial functions in temperate soils by increasing microbial biomass, enzyme activities, and nitrogen-fixing bacteria, but their effects are limited in semi-arid soils due to moisture constraints. While nano-fertilizers improve nutrient availability and crop productivity, high doses may induce microbial stress, particularly in water-limited systems. Management strategies should optimize nano-fertilizer doses and integrate moisture management to support soil health. Further studies are needed to assess long-term impacts and broaden applications across diverse agroecosystems.

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