Impact of Magnesium Nanoparticles on Nutrient Uptake and Yield Performance of Arid Crops: A Comparative Study on Moth Bean, Mung Bean, Cluster Bean, Pearl Millet and Sorghum

Reena Chouhan[1], **Amita Gharu Dhariwal**[2]

[1]Ph.D. scholar, Department of Chemistry, Jai Narain Vyas University, Jodhpur 342001, India
[2]Assistant Professor, Department of Chemistry, Jai Narain Vyas University, Jodhpur 342001, India

Abstract

The present study aimed to evaluate the effect of magnesium nanoparticles (Mg NPs) on the uptake of nitrogen (N), phosphorus (P), and sulphur (S) and the consequent yield performance of five major arid crops, namely moth bean (*Vigna aconitifolia*), mung bean *(Vigna radiata*), cluster bean (*Cyamopsis tetragonoloba*), pearl millet (*Pennisetum glaucum*), and sorghum (*Sorghum bicolor*). Field and controlled environment experiments were conducted following a randomized block design at the Research Farm, Jodhpur, Rajasthan, during the Kharif season. Magnesium nanoparticles were applied as foliar sprays at two concentrations (10 and 20 mg L^{-1}), and their effects were compared with an untreated control. The effects of Mg NP application on nutrient uptake (N, P, and S), enzymatic activities, plant growth, and yield attributes were systematically evaluated. The results demonstrated a significant enhancement in nutrient uptake across all crops treated with Mg NPs, with the highest increases in nitrogen and phosphorus uptake observed in leguminous crops, while sulfur uptake was more pronounced in pearl millet and sorghum. Yield improvement ranged from 18% in moth bean to more than 40% in pearl millet compared to the control treatment. Additionally, Mg NP application markedly improved chlorophyll content, root biomass, and key enzymatic activities such as acid phosphatase, nitrate reductase, and arylsulphatase, indicating improved nutrient mobilization and metabolic efficiency. Overall, the findings establish magnesium nanoparticles as a promising nano-fertilizer for arid and semi-arid cropping systems, offering a sustainable strategy to enhance nutrient use efficiency and crop productivity under nutrient-stressed conditions.

Keywords: Magnesium nanoparticles, Enzyme activity, Nutrient uptake, Yield enhancement, Arid crops, Nano-fertilizer

1. Introduction

Harsh climatic conditions and poor soil fertility limit agricultural production in arid and semi-arid regions. These soils are typically sandy, alkaline in reaction, and deficient in organic matter, which restricts the availability of essential nutrients such as nitrogen, phosphorus, and sulphur. Conventional fertilizers are often ineffective in these environments because nitrogen is easily lost through volatilization and leaching, phosphorus becomes fixed as insoluble calcium phosphates, and sulphur remains deficient due to weak microbial activity. This nutrient stress, together with limited water availability, reduces crop productivity and resource-use efficiency in arid cropping systems.

Magnesium is a vital nutrient in plant metabolism. It forms the central atom of the chlorophyll molecule and activates numerous enzymes that regulate nutrient uptake and assimilation. Magnesium deficiency reduces photosynthetic efficiency, disrupts enzyme function, and leads to nutrient imbalance. Providing magnesium in an effective form is therefore essential, especially in nutrient-stressed soils.

Nanotechnology is now being seen as a modern approach to address such limitations. Nanoparticles have a very small size and high surface area, which makes them more reactive than normal fertilizer materials. They can move easily in soil and plant systems, release nutrients, and improve the efficiency of fertilizer use. Nanoparticles provide new opportunities to improve fertilizer efficiency because of their high reactivity and controlled release properties (Liu & Lal, 2015; Solanki et al., 2015). Studies have shown that nanoparticle delivery systems can interact more effectively with plant tissues compared to bulk materials (Nair et al., 2010; Dwivedi et al., 2017).

Recently, the application of magnesium nanoparticles (Mg NPs) has provided a new approach for enhancing nutrient availability in stressed soils. Due to their nanoscale size and high surface area, Mg NPs can interact more effectively with plant roots and soil microorganisms compared to conventional sources, thereby improving nutrient solubility and uptake.

A growing body of research supports the potential of Mg NPs to stimulate plant growth and nutrient mobilization. Rathore and Tarafdar (2015) reported that foliar application of biosynthesized Mg NPs in wheat increased chlorophyll content, plant biomass, and nutrient concentrations, indicating improved nitrogen assimilation and photosynthetic activity. Similarly, Adhikari (2019) showed that maize treated with magnesium oxide nanoparticles exhibited greater phosphorus utilization efficiency due to enhanced acid phosphatase activity, which helped solubilize otherwise unavailable phosphorus fractions in alkaline soils. Other studies confirm that nanoparticles can enhance rhizospheric enzyme activity and nutrient uptake, as shown in cluster bean by Raliya and Tarafdar (2013), who observed increased secretion of phosphorus-mobilizing enzymes under ZnO nanoparticle treatment.

These findings suggest that Mg NPs could serve not only as a direct nutrient source but also as stimulants of enzyme-mediated nutrient release, thereby improving nutrient availability in poor soils. Considering the importance of crops such as moth bean (Vigna aconitifolia), mung bean (Vigna radiata), cluster bean (Cyamopsis tetragonoloba), pearl millet (Pennisetum glaucum), and sorghum (Sorghum bicolor) in arid agriculture, the present study was undertaken to assess the effect of Mg NPs on nutrient uptake and yield performance. By integrating controlled and field-level experiments, the research aims to provide insights into the practical utility of Mg NPs as a nano-fertilizer for dryland farming.

2. Materials and Methods

The present study was designed to examine how magnesium nanoparticles influence nutrient uptake and yield in five major crops of arid regions: moth bean (*Vigna aconitifolia*), mung bean (*Vigna radiata*), cluster bean (*Cyamopsis tetragonoloba*), pearl millet (*Pennisetum glaucum*), and sorghum (*Sorghum bicolor*).

2.1 Site Description

The field experiments were conducted at the Research Farm of Jodhpur, Rajasthan, situated in the hot arid region of northwestern India (26°18′ N latitude and 73°01′ E longitude). The climate of this region is typically arid, receiving an annual rainfall of only 250–300 mm, the majority of which occurs during the monsoon months of July to September. Summers are extremely hot, with maximum temperatures reaching around 45°C, while winters are comparatively cool with minimum temperatures dropping to nearly 6°C.

Table 1: Initial soil characteristics

Parameter	Value
pH	8.2
EC	0.27 dS/m
Organic carbon	0.23 %
Available nitrogen	118 kg/ha
Available phosphorus	6.8 kg/ha
Available sulphur	8.2 kg/ha
Soil Type	Sandy loam

Figure 1SEM analysis of MgO nanoparticles

Table 2: Crop details and varieties

Crop	Duration (days)	Season
Moth bean	70–80	Kharif
Mung bean	65–75	Kharif
Cluster bean	90–100	Kharif
Pearl millet	85–95	Kharif
Sorghum	100–110	Kharif

The experimental soil is classified as sandy loam (Typic Torripsamments), characteristic of arid zone soils. It is alkaline in nature, exhibits low organic carbon content, and is inherently deficient in available nitrogen, phosphorus, and sulphur. These soil constraints are typical of the hot arid zone of Rajasthan and significantly influence nutrient cycling, microbial activity, and plant growth responses.

2.2 Magnesium Nanoparticles

The magnesium oxide (MgO) nanoparticles used in the experiment were procured from a certified nanomaterial supplier to ensure reliability and experimental consistency. The nanoparticles had a particle size range of 20–60 nm and a purity level of ≥99% MgO, suitable for agricultural and soil–plant biochemical studies. To confirm the physicochemical properties, the nanoparticles were further characterized prior to their use. The foliar application of the MgO NPs solution was done after the ultrasonication of the solution.

2.3 Experimental Design

A Randomized Block Design (RBD) was employed to evaluate the effect of magnesium oxide nanoparticles (MgO NPs) on crop growth and nutrient uptake under arid soil conditions. The experiment consisted of three treatments, each replicated three times, and uniformly distributed across the field to minimize spatial variability.

T_1 – Control: No application of MgO nanoparticles.

T_2—Foliar application of MgO NPs @ 10 mg L^{-1} at 20 and 40 days after sowing (DAS).

T_3 – Foliar application of MgO NPs at 20 mg L^{-1} at 20 and 40 DAS.

2.4 Plot Layout and Agronomic Details

Each experimental plot measured 4 m × 3 m (12 m^2). Crop-specific spacing guidelines were followed to maintain uniform plant population and ensure agronomic consistency. All plots received a basal fertilizer dose equivalent to 50% of the recommended NPK, intentionally designed to simulate the nutrient-limited conditions typical of arid and semi-arid soils of Rajasthan. This approach helped assess the capacity of MgO nanoparticles to enhance nutrient availability and utilization under low-input conditions.

The magnesium oxide (MgO) nanoparticles used in the experiment were procured from a certified nanomaterial supplier to ensure reliability and experimental consistency. The nanoparticles had a particle size range of 20–60 nm and a purity level of ≥99% MgO, suitable for agricultural and soil–plant biochemical studies. To confirm the physicochemical properties, the nanoparticles were further characterized prior to their use. The foliar application of the MgO NPs solution was done after the ultrasonication of the solution.

2.5 Crop Management

Sowing was undertaken during the month of July, coinciding with the onset of the monsoon season. For leguminous crops, pre-soaked seeds were used to promote uniform and rapid germination, which is essential under the moisture-limited conditions of arid soils. Irrigation was kept to a minimum throughout the experiment. Only supplemental irrigation was applied at critical stages to prevent complete crop failure, ensuring that the crop response reflected the influence of MgO nanoparticle treatments under near-rainfed conditions typical of hot arid regions.

Weed management was carried out manually at 20 and 40 days after sowing (DAS) to maintain uniform competition levels across all plots. No chemical herbicides were used to avoid introducing confounding effects on soil biological parameters. Pest and disease management followed standard Integrated Pest Management (IPM) practices, including cultural and mechanical control measures. Importantly, no nutrient-containing pesticides or foliar supplements were applied to prevent interference with treatment effects and to maintain the integrity of nutrient response measurements.

2.6 Growth and Physiological Assessments

Plant growth and physiological responses to MgO nanoparticle treatments were assessed periodically from 28 DAS until harvest. Plant height was measured from the soil surface to the tip of the main shoot using a meter scale, and the average was calculated from five representative plants per plot. Vegetative growth was further assessed by recording the number of fully expanded leaves per plant. Leaf area index

(LAI) was estimated using standard non-destructive methods, with leaf area determined either by a leaf area meter or by length–width relationships.

Chlorophyll content was measured in vivo using an SPAD chlorophyll meter, with readings taken from the middle portion of fully expanded leaves. Root growth was evaluated by carefully excavating plants at designated sampling stages or at harvest, followed by measurement of root length and recording of fresh and oven-dried biomass after drying at 65°C.

2.7 Enzymatic Activities

Enzymatic activities associated with nitrogen, phosphorus, and sulphur cycling were determined from root and rhizosphere soil samples collected at 45 DAS. Acid and alkaline phosphatase activities were estimated using the method of Tabatabai and Bremner (1969), based on the release of p-nitrophenol from p-nitrophenyl phosphate substrate under appropriate pH conditions. Nitrate reductase activity was measured following Tiedje (1982), by quantifying nitrite production from nitrate in fresh root tissues. Arylsulphatase activity was estimated according to Chandramohan et al. (1974) using p-nitrophenyl sulphate as a substrate. Enzyme activities were expressed on a per gram soil or fresh tissue basis per hour**.**

2.8 Nutrient Uptake Analysis

At harvest, representative plant samples were collected, oven-dried, ground, and chemically analyzed for nitrogen, phosphorus, and sulphur content. Nitrogen concentration was determined by the Kjeldahl digestion–distillation method. Phosphorus content was analyzed using the vanadomolybdate yellow colorimetric method, while sulphur content was estimated turbidimetrically using barium chloride. Nutrient uptake was calculated by multiplying nutrient concentration with total dry matter yield and expressed in kg ha^{-1}.

2.9 Yield Attributes

Yield attributes were recorded at physiological maturity. In leguminous crops, the number of pods per plant, seeds per pod, 100-seed weight, grain yield, and straw yield were determined. In cereal crops, effective tillers, grains per ear head, 1000-grain weight, grain yield, and stover yield were recorded following standard agronomic procedures. All yields were expressed on a hectare basis after appropriate moisture correction.

2.10 Statistical Analysis

Experimental data were subjected to statistical analysis using analysis of variance (ANOVA) for Randomized Block Design as described by Gomez and Gomez (1984). Treatment means were compared at a significance level of $p \leq 0.05$. Pearson’s correlation analysis was performed to examine relationships between nutrient uptake and yield parameters, while regression analysis was employed to assess dose–response relationships between MgO nanoparticle application and crop yield**.**

3. Results and Discussion

The results from the field trials demonstrate clear trends in enzyme activity, nutrient uptake, and yield performance of the five arid crops following Mg nanoparticle (Mg NP) application. The findings are presented in a crop-wise manner, followed by comparative analysis.

3.1 Effect of MgO Nanoparticles on Growth Parameters

Application of magnesium oxide nanoparticles (MgO NPs) significantly influenced growth parameters of all five arid crops under study. Plant height, number of leaves, leaf area index (LAI), root length, and root biomass showed marked improvement with increasing doses of MgO NPs compared to the control.

Among treatments, foliar application of MgO NPs at 20 mg L^{-1} (T3) recorded the maximum enhancement in growth parameters, followed by 10 mg L^{-1} (T2), indicating a clear dose-dependent response.

Leguminous crops (moth bean, mung bean, and cluster bean) exhibited relatively higher improvement in vegetative growth compared to cereals, possibly due to their greater physiological plasticity and synergistic interaction between Mg availability and biological nitrogen fixation. In cereals, pearl millet and sorghum showed substantial improvement in root biomass and LAI, reflecting better adaptation to arid soil conditions under Mg NP supplementation. Similar enhancement in plant height, leaf area index, and biomass following magnesium supplementation has been reported earlier, owing to the role of Mg in chlorophyll synthesis, photosynthetic carbon fixation, and enzyme activation (Cakmak and Yazici, 2010; Hermans et al., 2004). Recent studies further suggest that nano-sized Mg improves nutrient use efficiency and metabolic activity in stress-prone environments (Rui et al., 2016).

Table 3: Improvement of different plant growth parameters in arid crops by the application of MgO NPs (mean values), *figure in parenthesis denotes the percent increment compare to control

Parameter	**Control (T_1)**	**10 mg L^{-1} (T_2)**	**20 mg L^{-1} (T_3)**
Plant height (cm)	68.4	74.9 (9.5)	81.7 (19.4)
Leaves / plant	18.6	21.8 (17.2)	25.4 (36.6)
Leaf Area Index (LAI)	2.12	2.48 (17.0)	2.89 (36.3)
Root length (cm)	19.3	22.6 (17.1)	26.8 (38.9)
Root dry biomass (g / plant)	4.6	5.3 (15.2)	6.2 (34.8)

Foliar application of MgO nanoparticles significantly enhanced vegetative growth, with improvements ranging from 9–17% at 10 mg L^{-1} and 19–39% at 20 mg L^{-1} over the control. The pronounced increase in root length and biomass indicates improved soil exploration capacity and nutrient absorption efficiency under Mg NP treatments.

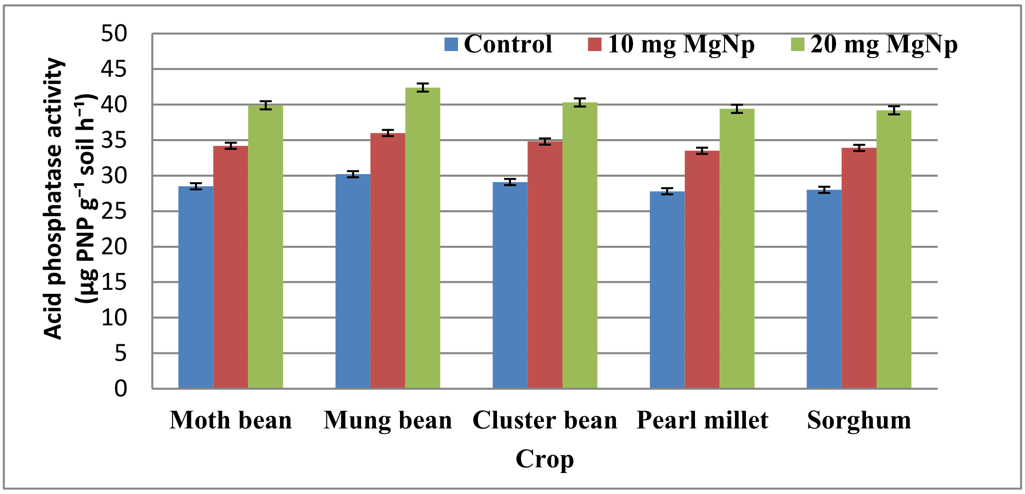
3.2 Effect of MgO Nanoparticles on Physiological Parameters

Physiological assessments revealed that MgO nanoparticle application significantly enhanced chlorophyll content across all crops. SPAD values increased progressively with increasing Mg NP concentration, with the highest readings observed under T_4 treatment. The improvement was more pronounced in pearl millet and sorghum, reflecting their higher demand for magnesium under rapid biomass accumulation. Similar increases in chlorophyll content following Mg-based nanoparticle application have been reported by Shaul (2002).

Table 4: Effect of MgO nanoparticles on chlorophyll content (SPAD values), *figure in parenthesis denotes the percent increment compare to control

Crop	Control	Mg NPs 10 mg L^{-1}	Mg NPs 20 mg L^{-1}
Moth bean	32.4	36.9 (13.9)*	41.8 (29.0)
Mung bean	34.1	38.2 (12.0)	43.6 (27.9)
Cluster bean	33.6	37.5 (11.6)	42.7 (27.1)
Pearl millet	36.8	41.6 (13.0)	47.9 (30.2)
Sorghum	35.9	40.8 (13.6)	46.3 (29.0)

Figure 2. Effect of Mg Nanoparticles on acid phosphatase activity in different crops after 45 DAS. Vertical bar represents LSD (p=0.05)



Acid phosphatase plays a critical role in mobilizing organic phosphorus in alkaline soils, and its stimulation under nanoparticle application has been widely reported (Tabatabai and Bremner, 1969). Raliya and Tarafdar (2013). A similar trend was observed with nitrate reductase. The Mg NP application enhanced nitrate reductase in all five crops. The improvement was most significant at 20 mg/L foliar spray levels. Application of MgO nanoparticles significantly enhanced nitrate reductase activity across all crops compared with the control. The 20 mg/L MgO NP dose produced the strongest response, showing a 33–36% increase in enzyme activity depending on the crop. Moth bean, mung bean, and pearl millet showed the highest enzymatic enhancement (>35%), indicating stronger nitrate reduction and improved nitrogen assimilation. The 10 mg/L treatment also increased activity but remained consistently lower than the 20 mg/L dose, confirming a dose-dependent stimulatory effect. Enhanced nitrate reductase activity under nanoparticle fertilization has also been reported in earlier studies, confirming improved nitrogen metabolism and assimilation efficiency (Ma and Wang, 2010; Shang et al., 2019).

Figure 3 Effect of Mg Nanoparticles on nitrate reductase activity in different crops after 45 DAS. Vertical bar represents LSD (p=0.05)

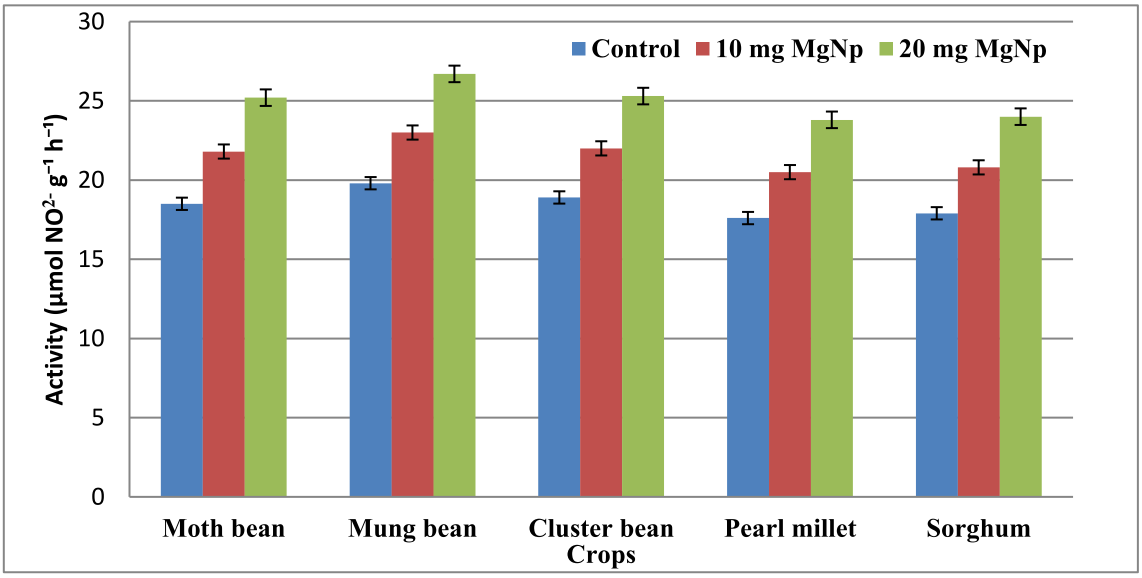
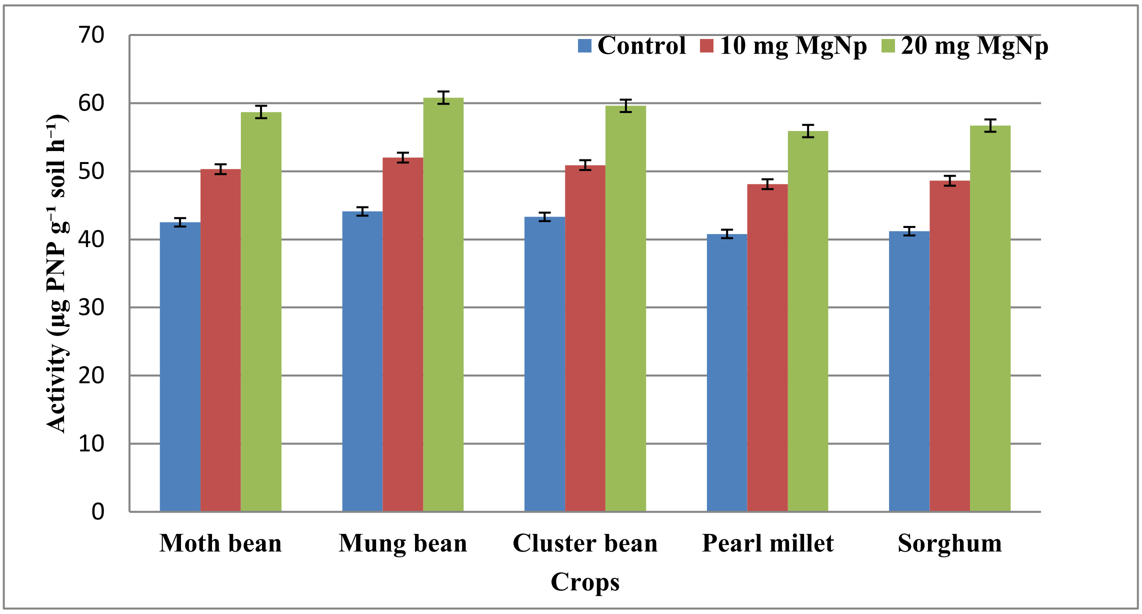


Figure 4. Effect of Mg Nanoparticles on arylsulphatase activity in different crops after 45 DAS. Vertical bar represents LSD (p=0.05)



The Mg NPs application enhanced arylsulphatase significantly in all five crops. The improvement was most significant at 20 mg/L foliar spray levels. The 20 mg/L dose produced a 35–40% increase, indicating strong stimulation of sulphur mineralization processes in the rhizosphere. Legumes (moth bean, mung bean, and cluster bean) showed slightly higher enzymatic response compared to cereals, suggesting more active root–microbial interactions. The 10 mg/L dose also improved activity, but the response remained clearly dose-dependent, with 20 mg/L giving maximum biochemical enhancement. Overall, MgO nanoparticles effectively boosted soil sulphur cycling capacity, supporting improved nutrient availability and crop growth under arid-zone conditions. Similar enhancement of sulphur-transformining enzymes under nanoparticle application has been reported by Rastogi et al. (2017) and Rui et al. (2016).

Overall, rhizosphere enzyme activities were significantly higher in Mg NP-treated plots compared to controls. This agrees with the work of Raliya and Tarafdar (2013), who demonstrated that nanoparticles enhance root exudation and enzyme secretion, leading to improved nutrient mobilization.

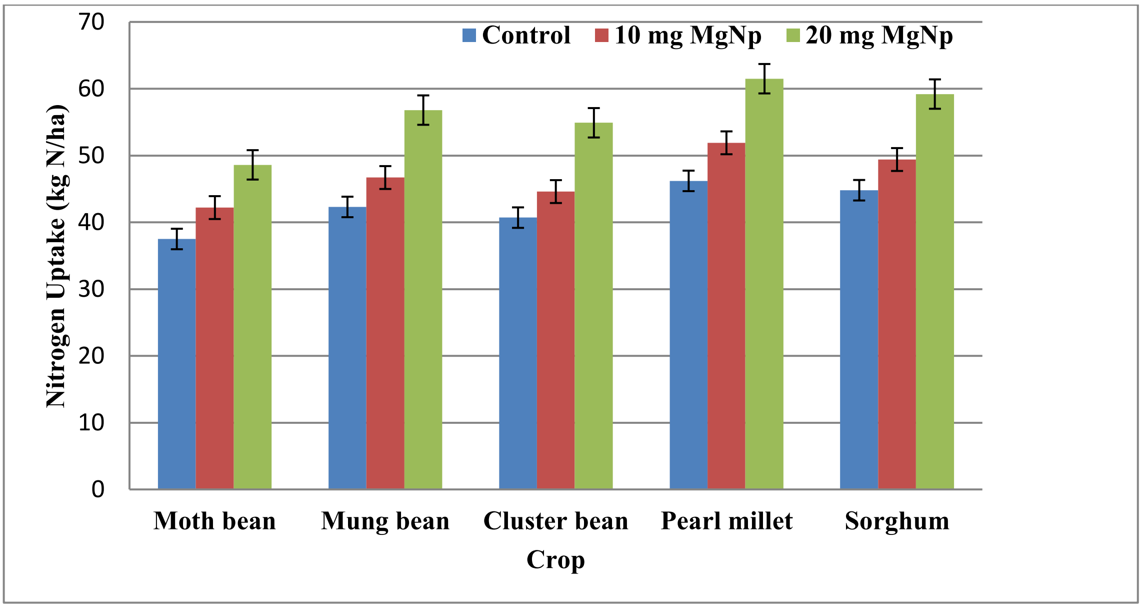
3.4 Effect on Nutrient Uptake

Mg NP application enhanced nitrogen uptake in all five crops. The improvement was most significant at 20 mg/L foliar spray levels. The increased N uptake aligns with the elevated nitrate reductase activity observed, confirming enhanced nitrogen assimilation. Legumes benefited from improved root nodulation, while cereals saw better leaf area development for efficient N utilization. This can be attributed to the role of magnesium as a cofactor for nitrate reductase, which facilitates nitrogen assimilation. The enhanced nitrogen assimilation under Mg NP treatment agrees with reports that nanoparticles stimulate enzymatic activity and nutrient transport in cereals (Ma & Wang, 2010; Shang et al., 2019).

Table 8: Percent improvement of nutrient uptake in different crop by the application of Mg NPs

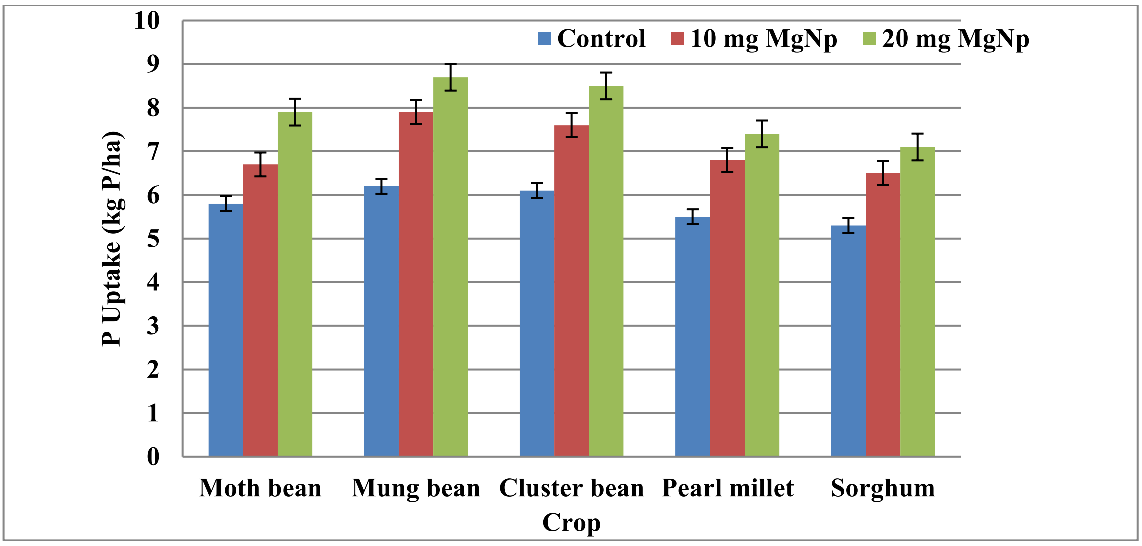
Crop	**% improvement in Nitrogen uptake**		**% improvement in phosphorus uptake**		**% improvement in sulphur uptake**	
	Mg NPs 10 mg/L	**Mg NPs 20 mg/L**	**Mg NPs 10 mg/L**	**Mg NPs 20 mg/L**	**Mg NPs 10 mg/L**	**Mg NPs 20 mg/L**
Moth bean	12.5	29.6	15.5	36.2	13.8	36.1
Mung bean	10.4	34.2	27.4	40.3	26.3	36.8
Cluster bean	9.5	34.9	24.6	39.3	15.4	35.9
Pearl millet	12.3	33.2	23.6	34.5	23.8	40.5
Sorghum	10.3	32.1	22.6	34.0	24.4	41.4

Figure 5. Nitrogen uptake by different crops at harvesting time. Vertical bar represents LSD (p=0.05)



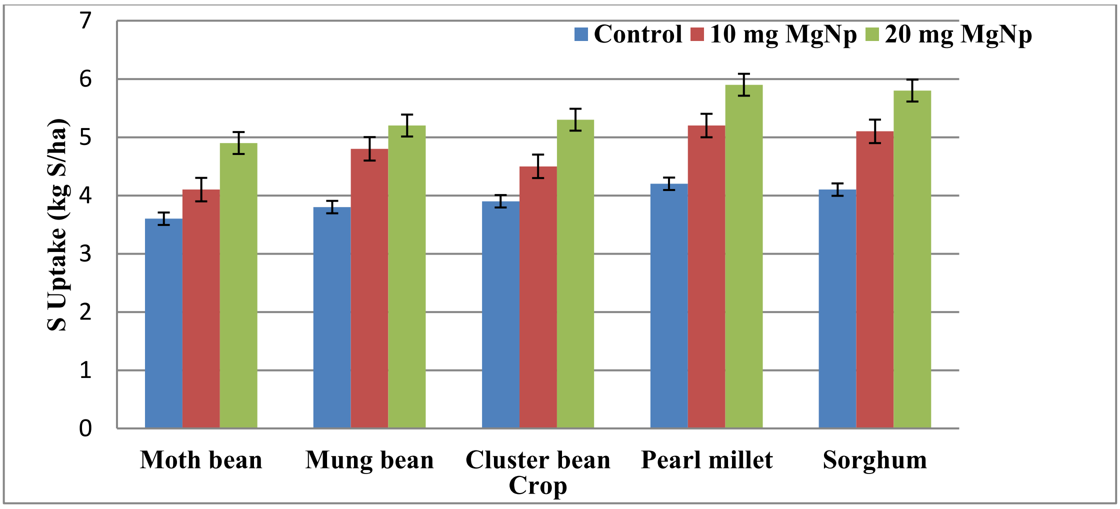
The application of Mg NPs boosted phosphorus uptake due to improved acid phosphatase and phytase activity. Enhanced phosphorus uptake was observed under Mg NP treatments, particularly in mung bean and cluster bean. This was likely due to stimulation of acid phosphatase activity, which releases phosphorus from insoluble compounds. Adhikari (2019) reported a comparable effect in maize, where Mg oxide nanoparticles increased phosphorus utilization efficiency through higher enzyme activity. The present findings confirm that Mg NPs act not only as a nutrient source but also as a catalyst for mobilizing unavailable phosphorus.

Figure 6. Phosphorus uptake by different crops at harvesting time. Vertical bar represents LSD (p=0.05)



Sulphur uptake also improved, with cereals showing slightly higher percentage increases than legumes**.** Significant increases in sulphur content were also recorded, especially in cereals like sorghum and pearl millet. Magnesium is known to stimulate arylsulphatase activity in soils, thereby improving sulphur mineralization. Similar findings were reported by Chandramohan et al. (1974) and later supported by studies on nanoparticle-mediated enzyme activation (Rastogi et al., 2017 & Rui et al., 2016)**.** These results highlight the role of Mg NPs in overcoming sulphur deficiencies typical of arid soils.

Figure 7. Sulphur uptake by different crops at harvesting time. Vertical bar represents LSD (p=0.05)



3.5 Yield Attributes and Grain Yield

The Application of MgO nanoparticles resulted in noticeable improvements in key yield attributes of legumes. The increase of 15–22% in pods per plant indicates enhanced vegetative and reproductive growth. The 10–15% rise in seeds per pod reflects better fertilization and seed-setting efficiency. Similarly, the 7–9% increase in 100-seed weight suggests improved nutrient translocation and seed filling. Overall, MgO NPs positively influenced reproductive performance, contributing to higher final yield.

MgO nanoparticle application significantly enhanced cereal yield components. The 18–21% increase in effective tillers indicates improved tiller initiation and stronger vegetative growth. The rise of 14–16% in grains per ear head reflects better flowering and grain-setting efficiency. Likewise, the 9–11% improvement in 1000-grain weight suggests enhanced nutrient accumulation and grain filling. Overall, MgO NPs improved both the number and quality of grains, contributing to higher cereal productivity.

Table 9: Effect of Mg Nanoparticles application on Crop Yield

Crop	**Control (kg/ha)** ***(Mean ± SE)***	**20 mg/L Mg NP** ***(Mean ± SE)***	**% Increase**
	Legumes		
Moth bean	630 ± 5.0	744 ± 4.4	18.1%
Mung bean	780 ± 5.8	986 ± 3.6	26.4%
Cluster bean	820 ± 5.3	1052 ± 5.3	28.3%
	Cereals		
Pearl millet	1813.3 ± 8.8	2586.7 ± 8.8	41.8%
Sorghum	1960.0 ± 5.8	2740.0 ± 5.8	39.8%

Table 10: Improvement in key yield attributes after application of MgO NPs

% Increase due to MgO NPs (20 Mg/L)	**Key yield attributes of legumes**		
	Pods / plant	**Seeds / pod**	**100-seeds weight**
	+15–22%	+10–15%	+7–9%
	Key yield attributes of cereals		
	Effective tillers	**Grains / ear head**	**1000-grains weight**
	+18–21%	+14–16%	+9–11%

Overall yield parameters, including grain weight, pod number, and biomass, showed substantial improvements under Mg NP treatments. Legumes such as mung bean and cluster bean responded with better nodulation and pod development, while cereals like pearl millet and sorghum recorded higher grain filling and test weight. These results are consistent with previous studies that reported yield gains under nanoparticle fertilization, including Li et al. (2013) in watermelon and Rossi et al. (2019) in soybean.

3.6 Comparative Crop Performance

The results showed that nutrient uptake and yield responses varied across crops. Mung bean and cluster bean exhibited the highest gains in nitrogen and phosphorus uptake, reflecting their strong physiological response to MgO nanoparticle application. In contrast, pearl millet and sorghum recorded the highest sulphur uptake, indicating enhanced sulphur assimilation efficiency in cereals. Among all crops, pearl millet showed the highest relative yield increase (+41.83. productivity boost under Mg NP treatment. Overall, mung bean displayed the most consistent improvement across all measured parameters, making it the most responsive crop to MgO nanoparticle application.

3.7 Optimal Dose Identification

Data from all five crops indicate 20 mg/L Mg NP foliar spray at 20 and 40 DAS as the most effective treatment for maximizing nutrient uptake and yield without phytotoxicity. Soil application at 25 mg/kg also showed benefits but was less cost-efficient. The observed improvements in nutrient uptake and yield across both legumes and cereals confirm the dual role of Mg NPs as a nutrient source and as a stimulator of soil–plant biochemical processes. These findings reinforce earlier reports (Juárez-Maldonado et al., 2019; Mittal et al., 2020) that nanoparticles enhance physiological efficiency and nutrient-use efficiency in crops. However, as noted by Tripathi et al. (2017), further long-term studies are necessary to assess persistence, environmental impacts, and economic feasibility before large-scale adoption. While the benefits are evident, concerns about the long-term persistence and environmental impact of nanoparticles remain important (Parisi et al., 2015; Tripathi et al., 2017). Hence, large-scale adoption requires careful evaluation of safety and cost-effectiveness.

4. CONCLUSION

The application of magnesium nanoparticles significantly enhanced nutrient uptake, plant biomass, and grain yield in both legumes and cereals. The foliar application of 20 mg/L Mg NPs was found to be most effective to improve chlorophyll synthesis and photosynthesis and provide indirect benefits through stimulation of root exudates and rhizosphere microbial activity. This research demonstrates that Mg NPs are a promising nano-fertilizer technology for improving the productivity of arid cropping systems, reducing dependence on high fertilizer inputs, and contributing to sustainable agriculture.

5. FUTURE SCOPE

Future research should focus on multi-season and multi-location field trials across diverse arid and semi-arid regions to ensure the long-term reliability and scalability of Mg nanoparticle (Mg NP) applications. Integrated nano fertilizer strategies combining Mg NPs with complementary nanoparticles such as ZnO, Fe_2O_3, and nano-hydroxyapatite should be explored to optimize nutrient delivery and crop nutritional balance. Additionally, comprehensive economic analyses are needed to assess cost–benefit ratios for large-scale farmer adoption, alongside environmental impact studies evaluating soil persistence, leaching, and ecological risks of repeated Mg NP use. The integration of Mg NP foliar applications with precision agriculture tools, particularly drone-based spraying systems, also warrants investigation to enhance application efficiency and uniformity.

Acknowledgement:

The authors gratefully acknowledge the Department of Chemistry, Jai Narain Vyas University, Jodhpur, for providing the laboratory facilities, field resources, and technical support necessary to complete this investigation.

References

1. Adhikari, T. (2019). Magnesium oxide nanoparticles effect on utilization of soil phosphorus by maize (Zea mays L.) plant. *International Journal of Current Microbiology and Applied Sciences* 8(10), 410–419.
2. Cakmak, I., and Yazici, A. M. (2010). Magnesium: A forgotten element in crop production. *Better Crops* 94: 23–25.

3. Chandramohan, D., Devendran, K., and Natrajan, R. (1974). Arylsulfatase activity in marine sediments. *Marine Biology* 27: 89–92.
4. Dwivedi, S., Saquib, Q., Al-Khedhairy, A. A., and Musarrat, J. (2017). Understanding the role of nanomaterials in agriculture. *Environmental Chemistry Letters, 15*(1), 19–29.
5. Gomez, K. A., and Gomez, A. A. (1984). Statistical Procedures for Agricultural Research (2nd ed.). Wiley.
6. Hermans, C., Johnson, G. N., Strasser, R. J., and Verbruggen, N. (2004). Physiological characterization of magnesium deficiency in sugar beet. *Journal of Experimental Botany* 55: 2153–2161.
7. Juárez-Maldonado, A., Ortega-Ortiz, H., Pérez-Labrada, F., Cadenas-Pliego, G., and Benavides-Mendoza, A. (2019). Nanoparticles and nanomaterials as plant biostimulants. *International Journal of Molecular Sciences*, 20(1), 162.
8. Li, J., Chang, P. R., Huang, J., Wang, Y., and Yuan, H. (2013). Physiological effects of magnetic iron oxide nanoparticles toward watermelon. *Journal of Nanoscience and Nanotechnology* 13(8), 5561–5567.
9. Liu, R., and Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Science of the Total Environment* 514: 131–139.
10. Ma, X., and Wang, J. (2010). Titanium dioxide nanoparticles affect corn growth by influencing nutrient uptake and photosynthesis. *Journal of Agricultural and Food Chemistry, 58*(5), 2589–2594.
11. Mittal, D., Kaur, G., Singh, P., Yadav, K., and Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent developments and future perspectives. *Nanomaterials*, 10(6), 1207.
12. Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., and Kumar, D. S. (2010). Nanoparticulate material delivery to plants. *Plant Science, 179*(3), 154–163.
13. Parisi, C., Vigani, M., and Rodríguez-Cerezo, E. (2015). Agricultural nanotechnologies: What are the current possibilities? *Nano Today*, 10(2), 124–127.
14. Raliya, R., and Tarafdar, J. C. (2013). ZnO nanoparticle biosynthesis and its effect on phosphorus-mobilizing enzyme secretion and gum contents in cluster bean (*Cyamopsis tetragonoloba L.*). *Agricultural Research*, 2(1), 48–57.
15. Rastogi, A., Zivcak, M., Sytar, O., Kalaji, H. M., He, X., Mbarki, S., and Brestic, M. (2017). Impact of metal and metal oxide nanoparticles on plant: A critical review. *Frontiers in Chemistry*, 5, 78.
16. Rathore, I., and Tarafdar, J. C. (2015). Perspectives of biosynthesized magnesium nanoparticles in foliar application of wheat plant. *Journal of Bionanoscience*, 9(2), 209–214.
17. Rossi, L., Fedenia, L. N., Sharifan, H., Ma, X., and Lombardini, L. (2019). Effects of foliar application of zinc sulfate and zinc nanoparticles in Glycine max. *Plant Physiology and Biochemistry*, 135, 160–166.
18. Rui, M., (2016). Effects of magnesium oxide nanoparticles on plant growth and photosynthesis. *Journal of Agricultural and Food Chemistry*, 64, 4290–4298.
19. Rui, M., Ma, C., Hao, Y., Guo, J., Rui, Y., Tang, X., and Xing, B. (2016). Iron oxide nanoparticles as a potential iron fertilizer for peanut (*Arachis hypogaea*). *Frontiers in Plant Science, 7*, 815.
20. Shang, Y., Hasan, M. K., Ahammed, G. J., Li, M., Yin, H., and Zhou, J. (2019). Applications of nanotechnology in plant growth and crop protection: A review. *Molecules, 24*(14), 2558.
21. Shaul, O. (2002). Magnesium transport and function in plants. *New Phytologist*:155, 151–166.

22. Solanki, P., Bhargava, A., Chhipa, H., Jain, N., and Panwar, J. (2015). Nano-fertilizers and their smart delivery system. In M. Rai, C. Ribeiro, L. Mattoso, and N. Duran (Eds.), *Nanotechnologies in food and agriculture*, 81–101.
23. Tabatabai, M. A., and Bremner, J. M. (1969). Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. *Soil Biology and Biochemistry*: 1, 301–307.
24. Tiedje, J. M. (1982). Denitrification. In A. L. Page, R. H. Miller, and D. R. Keeney (Eds.), Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties (pp. 1011–1026).
25. Tripathi, D. K., Singh, S., Singh, S., Pandey, R., Singh, V. P., Sharma, N. C., and Dubey, N. K. (2017). An overview on manufactured nanoparticles in plants: Uptake, translocation, accumulation and phytotoxicity. *Plant Physiology and Biochemistry*: 110, 2–12.
26. Tripathi, D. K., Singh, V. P., Singh, S., Kumar, A., Chauhan, D. K., and Prasad, S. M. (2017). Silicon nanoparticles more effectively alleviated arsenate toxicity than silicon in maize cultivars. *Plant Physiology and Biochemistry*: *110*, 70–81