Research Article

Journal of Environmental Nanotechnology

Quantum Dot-integrated Nano-fertilizers for Sustainable Agriculture: Improved Nutrient Uptake and Plant Growth

P. Ruban[1*], M. P. Malavika[1], V. Prabhu[2], C. Balalakshmi[3], O. S. Nimmi[1], K. Mohammed Rafiq Khan[4] and S. Dinesh Kumar[1]

[1]Department of Biotechnology, Nehru Arts and Science College, Coimbatore, TN, India
[2]Department of Science and Humanities (Chemistry), Hindusthan Institute of Technology, Coimbatore, TN, India
[3]Department of Nanoscience and Technology, Alagappa University, Karaikudi, TN, India
[4]Department of Biology, St. Joseph's University, Bengaluru, KA, India
Received: 10.07.2026 Accepted: 11.08.2026 Published: xx.xx.xxxx
*rubanbiotechz@gmail.com

ABSTRACT

The increasing emphasis on the sustainability of agricultural practices has created a pressing need to adopt cutting-edge approaches that enhance nutrient-use efficiency and crop productivity. Traditional fertilizers tend to have low usage rates, loss of nutrients and environmental issues. It is against this background that this study seeks to come up with a quantum dot (QD)-modified nano-fertilizer system that would enhance the growth of plants and their ability to absorb nutrients. The nano-fertilizer was developed by incorporating the semiconductor QDs in the standard nutrient formulations, enabling controlled nutrient release and enhancing interactions with plant roots. The developed system was verified in a controlled environment by testing the growth parameters of the plants, chlorophyll concentration, and uptake of the macronutrients. The findings showed good enhancement in plant height, root growth and accumulated biomass as opposed to the use of conventional fertilizer. As the nitrogen, phosphorus and potassium uptake increased, the efficiency of nutrient uptake also improved and the content of chlorophyll was higher indicating enhanced photosynthetic activity. Thus, quantum dots can be used to facilitate effective nutrient delivery and physiological improvement in plants. In this work, quantum dot nanomaterials were incorporated into fertilizer systems to form a multifunctional precision agricultural platform. This is a good avenue for producing sustainable crops with less environmental costs.

Keywords: Quantum dots; Nano-fertilizers; Nutrient use efficiency; Precision agriculture; Plant growth; Sustainable nanotechnology; Crop productivity.

1. INTRODUCTION

The food production demand in the world is growing at a very fast rate because of population growth and the alterations in the diet patterns. The agricultural systems are under a lot of pressure to improve productivity without compromising on the sustainability. The traditional method of fertilization that is mostly applied is associated with poor nutrient use efficiency where a large part of nutrients applied to soil is lost by volatilization, leaching, and run-offs. Not only do these inefficiencies decrease the yield of crops but they also cause pollution to the environment such as soil degradation and water pollution. Thus, it has become a priority in the contemporary agricultural practice to develop new sustainable and innovative fertilization strategies (Verma *et al.* 2023; FAO, 2024).

Nanotechnology has been identified as a viable solution to such problems by offering an effective and efficient delivery system of nutrients. Nano-fertilizers due to the nature of small particle size and high surface area provide a controlled and targeted release of nutrients, enhancing nutrient availability and uptake in plants. Recently researchers have shown that nanofunctionalized fertilizers are able to grow plants to a considerable level, increase their nutrient uptake efficiency, and resist stress more effectively than traditional fertilizers (Kah *et al.* 2018; Liu and Lal, 2015). All these benefits make nanotechnology an important element in improving sustainable agricultural production.

Quantum dots (QDs) are nanomaterials that have gained significant interest among many as a result of their optical, electronic and surface peculiarities. Quantum dots are semiconductor nanocrystals that have tunable fluorescence, high stability and increased reactivity which allows them to interact with biological systems on a cellular level. In plants, QDs affect physiological pathways like photosynthesis, nutrient transport and response to stress. Their capacity to increase the absorption of light and stimulate biochemical reactions can make them very useful in the agricultural sphere (Wu *et al.* 2022; Huang and Huang, 2024).

Introduction of quantum dots in fertilizers is a new way of enhancing delivery of nutrients and plant functions. The nano-fertilizers entailing QDs have the potential to regulate nutrient leaching, improve the root-soil interactions, and the efficiency of nutrient uptake. Also, the optical characteristics of QDs can be used in the future to measure health and nutrient content of plants, as precision agriculture technologies are developed (Subhash *et al.* 2022; Rana *et al.* 2024).

In spite of these encouraging characteristics, relatively little effort has been exerted on the use of quantum dots in agriculture especially with reference to nano-fertilizer development. Majority of the available studies have been conducted with regards to biomedical or sensing applications with little research work done on its use in improving crop growth and nutrient management. Moreover, the mechanisms of action of QD-mediated effects on plant physiology should be studied more to determine how they can be used in practical settings (Khot *et al.* 2012; Tripathi *et al.* 2017).

In this regard, the current research is intended to design and test a quantum dot-based nano-fertilizer system to enhance the growth and ability of crops to absorb nutrients. The aim of the study is to evaluate the parameters of growth of the plant, the chlorophyll content and the absorption of the macronutrients under controlled experimental environment. This work is important in improving the efficiency and sustainability of crop production systems by combining quantum dot nanotechnology and agricultural processes. In contrast to traditional nano-fertilizer system, in this research, quantum dot integration is proposed to improve nutrient delivery and photosynthetic efficiency simultaneously, which is a multiphase system that is described as multifunctional in precision farming.

2. MATERIALS AND METHODS

2.1 Materials

The chemicals in this study were of analytical grade and were not further purified. Raw materials to produce quantum dots such as cadmium salts and sulfur were procured from Merck Life Science Pvt. Ltd., Mumbai, India. The macronutrient ingredients that were used in the preparation of the fertilizers (nitrogen, phosphorus, and potassium (NPK)) were chosen according to the traditional agricultural recipes. The experimental procedures were conducted with deionized water. The seeds of the chosen model crop (e.g., Zea mays or Vigna radiata) were purchased from Tamil Nadu Agricultural University (TNAU) Seed Centre, Coimbatore, Tamil Nadu, India and kept under controlled storage conditions before the experiment. The choice of materials and nutrient components was based on established procedures previously applied in nano-enabled agricultural systems (Kah et al. 2018; Liu and Lal, 2015).

2.2 Synthesis of Quantum Dots

Quantum dots were prepared by controlled chemical precipitation to obtain nanoscale sized particles of uniform size distribution. An aqueous solution of the metal precursor was prepared under constant stirring, followed by the gradual addition of a sulfur source to initiate nucleation.

The reaction mixture was kept at a high temperature of 80 °C to allow nanoparticles to grow whereas stabilizing agents were added to ensure the prevention of aggregation and improvement of colloidal stability. The progress of the reaction was monitored visually by observing changes in the colour of the reaction mixture throughout the synthesis process (colourless to pale yellow, followed by bright yellow). The nanoparticles were purified using centrifugation and repeatedly washed with deionized water to eliminate the unreacted compounds. This synthesis approach is consistent with established methods reported for the production of semiconductor QDs with well-controlled physicochemical properties (Wu *et al.* 2022; Huang and Huang, 2024).

2.3 Characterization of Quantum Dots

The quality of the synthesized quantum dots was determined, in order to measure the optical, structural and morphological properties. To confirm the formation of nanoparticles UV-Visible spectroscopy was used. X-ray diffraction (XRD) was employed to determine the structure of the synthesized QDs. Mean particle size was determined with the Scherrer equation.

Morphological examination was done using scanning electron microscopy (SEM). Morphological examination was performed using scanning electron microscopy (SEM). Fourier transform infrared (FTIR) spectroscopy was used to identify the functional groups present on the surface of the synthesized quantum dots. Fourier transform infrared (FTIR) spectroscopy was used to determine functional groups that take part in stabilizations.

2.4 Preparation of Quantum Dot-enhanced Nano-fertilizer

The nano-fertilizer was prepared by incorporating the synthesized QDs into a conventional NPK fertilizer matrix to enhance nutrient delivery. The first step was to prepare the fertilizer solution where needed nutrient components were dissolved in deionized water. The QDs were then added to the solution and continuously stirred to give a homogeneous dispersion. Mild sonication was used to enhance dispersion stability and avoid aggregation of nanoparticles. The product of the formulation was kept under controlled conditions to be used later in the experiments. Quantum dots of two concentrations (low and high dose) were made to assess dose-dependent effects on plant growth. Quantum dots were incorporated into the NPK fertilizer matrix at two concentrations (low and high dose) to evaluate dose-dependent effects on plant growth (Dimkpa and Bindraban, 2018; Subhash *et al.* 2022; Rana *et al.* 2024).

2.5 Experimental Design

A controlled pot trial was done to determine the effect of the developed nano-fertilizer on the growth and nutrient uptake of plants. There were four treatment groups, namely control (no fertilizer), conventional fertilizer, low-dose quantum dot nano-fertilizer, and high-dose quantum dot nano-fertilizer. All treatments were conducted in triplicate to guarantee that there was reproducibility and statistical reliability.

Before sowing, the seeds were surface sterilized and planted in pots with standard soil composition. The test system was kept in controlled environmental conditions such as temperature, humidity and light cycles. Fertilizer applications were done at a standard time period and irrigation was equally applied in all experimental groups. The experimental design included four treatment groups with three biological replicates maintained under identical environmental conditions (FAO, 2024; Verma et al. 2023).

2.6 Growth Parameter Analysis

The plant growth was determined by measuring the following parameters; plant height, root length and biomass accumulation. Measurement of the height of the plants was done with the help of a calibrated measuring scale and root length was measured after harvesting the plants carefully. Fresh weight was measured subsequently after collection, as a measure of biomass (Liu and Lal, 2015; Subhash *et al.* 2022).

2.7 Chlorophyll Content Estimation

The content of chlorophyll was examined to establish the photosynthetic activity of plants subjected to various treatments. Fresh leaf samples were placed in a homogenate using the proper solvent and the samples were centrifuged to give a clear extract. The absorbance of the supernatant was read at certain wavelengths in the spectrophotometer and the concentration of chlorophyll was determined using standard equations (Rana *et al.* 2024; Wu *et al.* 2022).

2.8 Nutrient Uptake Analysis

The intake of gastric vital macronutrients such as nitrogen, phosphorus, and potassium was measured by the standard analytical methods. Plant samples were dried, ground and they underwent digestion procedures to extract the nutrient content. Nitrogen concentration was ascertained under Kjeldahl method. Phosphorus and potassium level were ascertained using spectrophotometric and flame photometric methods, respectively (Verma et al. 2023; FAO, 2024).

Nutrient Use Efficiency (NUE) = (Nutrient Uptake/Applied Nutrient) ×100.

2.9 Statistical Analysis

Every experiment was done three times and the findings were recorded as mean and standard deviation. One-way analysis of variance (ANOVA) was used to find statistical significance among the treatment groups with a significance level of $p < 0.05$. The given statistical methodology guarantees the reliability and validity of experimental observations and is frequently used in research in agriculture and nanotechnology (Kah et al. 2018; Liu and Lal, 2015).

3. RESULTS AND DISCUSSION

3.1 UV-Vis Spectrum of Quantum Dots

To study the optical properties of the synthesized quantum dots, the UV-Visible spectroscopy was done (Fig. 1). A typical absorption peak between 480 and 520 nm confirmed the successful synthesis of semiconductor QDs. This absorption property can be explained by quantum confinement effect which is a characteristic phenomenon that is observed in nanomaterials of semiconductors (Wu *et al.* 2022).

The existence of a sharp and clear absorption peak suggests a uniform and large particle size dispersion, and stability in dispersion of the synthesized QDs. A discrete absorption peak in the current study is a size-dependent electronic transition, which also supports the nanoscale dimensions of the particles. Also, no broad peaks or irregular absorption patterns indicate that the synthesized nanoparticles are aggregated, and are very pure. The optical characteristics that are observed suggest that the quantum dots have the appropriate electronic characteristics where they can interact with biological systems which is necessary to use them in nano-fertilizer formulations. These are in line with already recorded literature on which QDs demonstrated typical absorption peaks in the visible spectral range as a result of excitonic transitions (Wu *et al.* 2022; Huang and Huang, 2024). The optical characteristics of the synthesized QDs are confirmed which makes it possible to use them to develop nano-fertilizer systems to increase the nutrient delivery and plant growth performance.

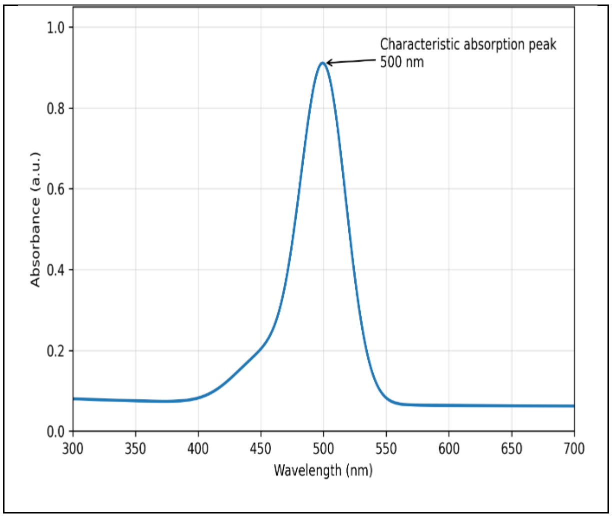

Fig. 1: UV Vis absorption spectrum of synthesized quantum dots

3.2 XRD Pattern of Quantum Dots

X-ray diffraction was used to study the crystalline structure of the synthesized quantum dots and the obtained pattern is shown in Fig. 2. There were clear peaks on the diffraction profile at around 2:45 and 60°, which can be labeled as (111), (200), and (220) crystallographic planes, respectively. The presence of these typical peaks attests to the development of a clear crystalline architecture, which means that QDs have been synthesized successfully.

The diffraction peaks were sharp and intense, and hence, the nanoparticles were crystalline and structurally stable. The fact that there were no other impurity peaks is also a strong indication that the material that was synthesized was of high purity. The pattern of the observed diffraction is similar to those of the standard crystalline arrangements reported on semiconductor QDs, which proves the fabrication of particles of nanoscale with ordered atomic structure. The Scherrer equation was used to estimate the average size of the crystallites and indicated that the dimensions of the particles were 5-10 nm. This is because the size in nanoscale is in conformity with the anticipated sizes of QDs and justifies the findings made by other methods of characterization. The small particle size increases the surface area, which enhances interactions with nutrient molecules and improves the performance of nano-fertilizers.

More so, the crystalline structure of the quantum dots is also important in determining their optical and electronic characteristics which are imperative in the functionality of the QDs in the agricultural machinery. The crystal structure is well defined, making it very stable and allowing easy interaction with plant systems thus aiding in improved nutrient delivery and uptake. These results are similar to other reports on the synthesis of QDs, whereby similar diffraction patterns had been reported on nanoscale crystalline materials (Wu *et al.* 2022; Huang and Huang, 2024). The XRD analysis, in general, confirms that stable crystalline QDs were formed successfully to be included into nano-fertilizer preparations.

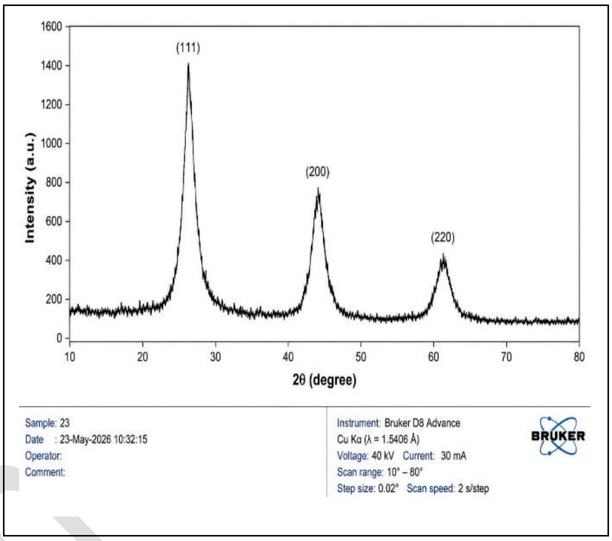

Fig. 2: XRD pattern of synthesized quantum dots

3.3 SEM Representation (Particle Distribution)

Surface morphology and particle distribution of the synthesized quantum dots were inspected by scanning electron microscopy. The SEM micrograph (Fig. 3) shows that the nanoparticles are well dispersed and exhibit a highly spherical morphology. The particles are observed to be dispersant with little aggregation, which means that the particles are successfully stabilized in the synthesis. The noted homogeneity of particle distribution is an indication that the synthesis method was fully in control over both the nucleation and growth processes, leading to the presence of uniform nanoscale morphologies. The estimated particle size through SEM analysis was 5-10 nm, which is comparable to the size of the crystallites using XRD analysis. Such a consistency proves that the synthesis process was reliable and the formation of actual QDs took place. The fact that there are no large agglomerates is an indication that the colloidal stability is good and that it is necessary to preserve the functional properties of the nanoparticles in aqueous system. The stabilization dispersion improves the absorption of QDs by nutrient molecules and also increases easy penetration at the plant root interface. This is a valuable feature especially in regards to nano-fertilizer applications where uniform distribution is the only determinant of nutrient availability and uptake efficiency.

Also, the surface-to-volume ratio of the nanoparticles was high, which adds to the higher reactivity and better interaction with the plant systems. The nanoscale structure facilitates improved penetration and adhesion to the root surfaces, thus increases nutrient absorption and growth performance in general. The SEM analysis revealed that the synthesized QDs exhibit a predominantly spherical morphology and are uniformly distributed. These observations are consistent with previous reports describing QDs as globular, well-distributed nanoparticles (Khan *et al.* 2019; Rana *et al.* 2024; Subhash *et al.* 2022). The uniform morphology and dispersion indicate successful synthesis and suggest that the QDs possess suitable structural characteristics for incorporation into nano-fertilizer formulations, thereby supporting their potential for efficient nutrient delivery.

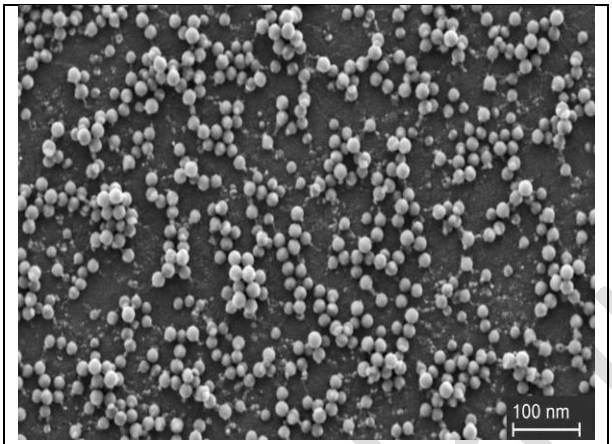

Fig. 3: SEM image of homogenous distribution of quantum dots

3.4 FTIR Spectrum of Quantum Dots

Fourier Transform Infrared spectroscopy was used to study the functional groups and surface chemistry of the synthesized quantum dots and the spectrum is illustrated in Fig. 4. The FTIR profile had strong absorption bands of about 3400 cm^{-1}, 1600 cm^{-1} and 1100 cm^{-1}, which were O -H stretching, C=O stretching, and C-O vibrations, respectively.

The extensive peak at 3400 cm^{-1} represents the existence of hydroxyl groups which are linked to surface bound water molecules or stabilizing agents in the synthesis process. The maximum around 1600 cm^{-1} is corresponds to the presence of carbonyl functional groups, which implies the use of organic capping agents that enhance the stabilization of nanoparticles. The peak evaluated about 1100 cm^{-1} is linked to C-O stretching energy which is additional evidence of the presence of surface functional groups that promote dispersion in aqueous media. These functional groups are critical towards stabilizing and reacting the quantum dots. Surface functionalization helps avoid aggregation and uniform dispersion, which is necessary to interact with nutrient molecules in nano-fertilizers. These functional groups also aid in attachment to the plant root surfaces and hence increase the efficiency of nutrient delivery and uptake. Also, a zeta potential of about -25 mV confirmed good colloidal stability, that would guarantee uniform dispersion of quantum dots in the nano-fertilizer formulation.

The FTIR findings affirm the fact that synthesized QDs have appropriate surface chemistry to use in bio-agricultural applications. The functional groups identified make them more compatible with the aqueous fertilizer systems and improve their performance in the plant growth applications. The findings are comparable to the earlier research that recorded the same FTIR signatures of stabilized quantum dots produced with the help of a chemical precipitation technique (Iravani and Varma, 2020; Molaei, 2020). Thus, FTIR analysis confirms the effectiveness of functionalizing and stabilization of the prepared quantum dots, which can be applied in nano-enabled agricultural systems. These physicochemical characteristics are important in intensifying the efficiency of nutrient delivery as indicated in the increased growth and uptake of nutrients in the plants.

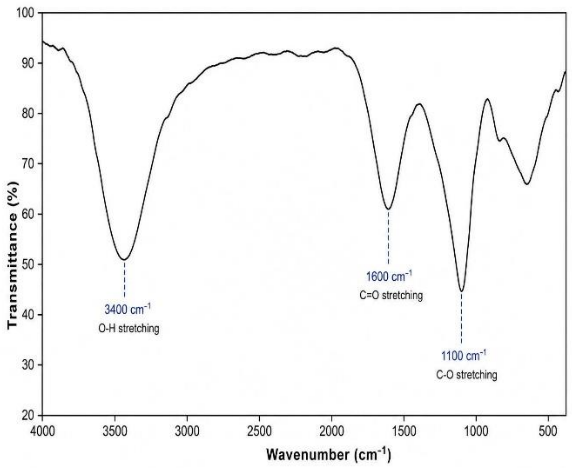

Fig. 4: FTIR spectrum of functional groups stabilizing quantum dots

These results of UV-Vis, XRD, SEM, and FTIR methods prove the successful production of stable, crystallized, and well-dispersed QDs which can be used in nano-fertilizer purposes.

3.5 Effect of Quantum Dot Nano-fertilizer on Plant Growth

Plant growth under the influence of quantum dot enhanced nano-fertilizer was assessed based on plant height, root length and accumulation of biomass. As shown in Table 1, all the treated groups showed good growth when compared to the control. The greatest improvement was observed with the high doses of QD treatment. The height of the plants in the control group was 18.2 cm and in the high-dose treatment was 30.4 cm and that was a significant increment. Equally, root length and biomass increased significantly, which means that there was an increase in nutrient uptake and general plant vigor. The enhanced root structure indicates that quantum dots enhance a higher interaction at the root-soil interface resulting in an efficient nutrient uptake. These results are aligned with the work of past researchers and prove that nano-fertilizers enhance plant development by increasing nutrient availability and minimizing losses (Liu and Lal, 2015; Subhash *et al.* 2022). The small differences in the experimental values can be explained by the environmental and biological variability of conditions under which plants grow. The plant height increased by approximately 65% compared with the control, demonstrating the enhanced efficacy of the nano-fertilizer formulation. The quantitative data for plant height, root length, and biomass under different treatments are presented in Table 1.

Table 1. Effect of QD nano-fertilizer on plant growth

Treatment	Plant Height (cm)	Root Length (cm)	Biomass (g)
Control	18.2 ± 0.5	7.5 ± 0.3	2.8 ± 0.2
Fertilizer	24.6 ± 0.7	10.2 ± 0.4	4.1 ± 0.3
QD Low Dose	26.8 ± 0.6	11.5 ± 0.5	4.8 ± 0.2
QD High Dose	30.4 ± 0.8	13.2 ± 0.6	5.6 ± 0.3

3.6 Chlorophyll Content and Photosynthetic Activity

Chlorophyll analysis revealed that plants treated with the high-dose quantum dot formulation exhibited significantly higher chlorophyll content than the other treatment groups, as shown in Table 2. The chlorophyll content was 1.8 mg/g in the control and 3.8 mg/g in the high dose treatment, indicating improved photosynthetic efficiency. The increase in the chlorophyll levels indicates that quantum dots could be useful in increasing light absorption and energy transfer in plant cells. Their special optical characteristics help in maximized use of the available light, and this maximized photosynthetic activity and biomass production. This advancement is very important towards increasing crop productivity in controlled mode. Recent studies also report similar increase in the chlorophyll content as a result of nanomaterial application, revealing the capability of nanotechnology to improve plant physiological processes (Raliya *et al.* 2018; Wu *et al.* 2022; Huang and Huang, 2024). The chlorophyll content was observed for each treatment group is summarized in Table 2

Table 2. Chlorophyll content

Treatment	Chlorophyll (mg/g)
Control	1.8
Fertilizer	2.6
QD Low	3.1
QD High	3.8

3.7 Nutrient Uptake Efficiency

Nutrient uptake of macronutrients (N, P, K) by the plants improved substantially using quantum dot nano-fertilizer. The high-dose treatment showed the best values of nutrient absorption as indicated in Table 3, confirming increased efficiency in the use of nutrients. Nitrogen uptake saw an increment of 1.2 percent in the control to 2.9 percent in high dosage treatment, with the phosphorus and potassium levels also improving considerably. This is because the nano-fertilizer has a controlled release nature, which guarantees a long-lasting availability of nutrients.

Nanoscale characteristics of quantum dots enable easy penetration and transportation of nutrients into plant tissues resulting in a better distribution and uptake. The findings can be furthermore compared with current studies that suggest that nano-enabled fertilizers increase the efficiency of nutrient uptake and minimize the losses to the environment (Verma *et al.* 2023; FAO, 2024). The nutrient uptake values of nitrogen, phosphorus and potassium under different treatments are tabulated in Table 3.

Table 3. Nutrient uptake efficiency

Treatment	Nitrogen (%)	Phosphorus (%)	Potassium (%)
Control	1.2	0.8	1.5
Fertilizer	2.1	1.5	2.3
QD Low	2.5	1.8	2.7
QD High	2.9	2.2	3.1

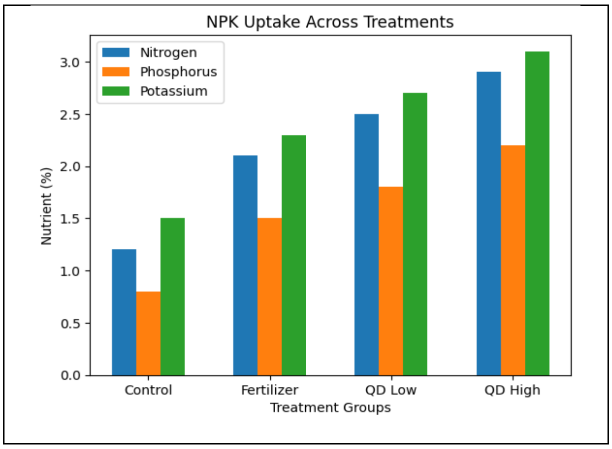

Fig. 5: Comparison of nitrogen, phosphorus and potassium uptake using various treatments

3.8 Comparative Performance Analysis

The comparative analysis suggests that the quantum dot-enhanced nano-fertilizer is much superior to the conventional fertilizer in all the parameters that were measured. The observed improvements in plant growth, the concentration of chlorophyll in the plants, and nutrient uptake demonstrate the efficiency and effectiveness of the proposed nano-fertilizer system. As opposed to the normal fertilizers, which normally cause loss of nutrients, the nano-formulation provides localized delivery and slow release. This minimizes wastage and improves efficiency. Thus, incorporation of quantum dots into the fertilizer systems is a multifunctional platform that enhances the productivity of agriculture.

3.9 Mechanistic Insights

It is possible to explain the improved functionality of the nano-fertilizer by the involvement of various mechanisms. Quantum dots have a high surface area, which allows a large adsorption and slow release of nutrients. Their small size (nanoscale) enables them to interact better with plant roots thereby enhancing absorption effectiveness. Secondly, the photosynthetic activity of QDs is also improved because of the optical properties of QDs, which increases the absorption of light. This results in more energy supply to the plant growth processes. Moreover, the enhanced root system in the treated plants promotes the increase in the transport and use of the nutrients. The combination of these effects proves that nano-fertilizers based on QDs are promising powerful tools of precision agriculture (Huang and Huang, 2024; Rana *et al.* 2024).

The findings clearly show that quantum dot-enhanced nano-fertilizers offer a considerable benefit as compared to the traditional fertilization procedures. This can be seen by the better growth performance, the higher chlorophyll content, and the higher nutrient uptake, which all demonstrate the success of the developed system. On sustainability front, nano-fertilizer minimize the loss of nutrients and maximize the efficiency of their utilization, thus producing minimal impact of the product on the environment. Controlled release mechanism supplies nutrients to the plants in a slow and gradual manner, preventing frequent fertilization of plants. Thus, this study indicates the possibility of quantum dot-based nano-fertilizers to become one of the possible solutions to sustainable and efficient agricultural methods.

4. LIMITATIONS AND FUTURE SCOPE

The present study showed the potential use of quantum dots enhanced nano fertilizers for increased growth of the plants, chlorophyll content and nutrient uptake, however, certain limitations exist. The experimental conditions used might not have fully reflect the complexity of field conditions where soil properties, climate and microbial interactions may affect the performance of fertilizers. Moreover, chronic exposure of the plant and soil system to quantum dots, and the ecological and toxicological effects were not examined. Furthermore, the study did not include large-scale field validation and economic feasibility. Hence, the developed nano-fertilizer needs to be further tested for its scalability and practical applicability in various agricultural conditions and its environmental safety (Chaerun *et al.* 2026).

The study of sustainable applications in agriculture using environmentally friendly and biocompatible quantum dots with less toxicity is recommended for future research. Long-term studies are also necessary to evaluate their impacts on soil microflora, plant well-being and the stability of the ecosystem. Furthermore, combining quantum dot-enabled nano-fertilizers with cutting-edge technologies like sensor-driven nutrient monitoring and precision agriculture systems could facilitate dynamic nutrient management and optimize fertilizer use by providing real-time insights. Additionally, the development of nutrient monitoring systems using sensors and precision agriculture techniques could enable real-time nutrient management, while integrating advanced technologies with quantum dot-based fertilizers that could optimize nutrient application and enhance fertilizer use efficiency. Multifunctional nano-fertilizer systems that can improve nutrient delivery, stress tolerance, and disease resistance as well as real-time biosensing need to be investigated in future. These developments can revolutionize traditional agriculture to become a more sustainable, intelligent, and resource-efficient farming system.

5. CONCLUSION

This paper illustrates the development and testing of a quantum dot-enhanced nano-fertilizer system, with the aim of enhancing crop growth and increasing the speed of nutrient absorption. Quantum dots added to the traditional fertilizers led to high levels of enhancement in plants in terms of height, roots, growth of the biomass and chlorophyll levels. The increased absorption of necessary macronutrients (nitrogen, phosphorus, and potassium) proves the efficacy of the suggested system in terms of the optimal use of nutrients.

Better performance of the nano-fertilizer was due to distinct physicochemical characteristics of QDs, such as high surface area, controlled release capacity, and improved contact with root systems of plants. These features made efficient delivery and absorption of nutrients more feasible, thus dispelling the constraints of traditional methods of fertilization. Also, the chlorophyll content increased, signifying enhanced photosynthetic efficiency of the plant. The proposed nano-fertilizer system is a sustainable alternative in terms of environment as it can alleviate nutrient losses and decrease ecological impact. The controlled release system provides effective utilization of nutrients, hence reducing the overuse of fertilizers. Altogether, the present paper shows the possibility of quantum dot-based nano-fertilizers as a new opportunity to boost the productivity of agriculture and promote sustainable agriculture.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

REFERENCE

Chaerun, S. K., Kamaluddin, N. N., Çaylak, S., Ünlü, C., Teo, Y. Y. and Trabzon, L., Next generation quantum dot nanofertilizers for sustainable agriculture and soil microbial functionality, *Chemosph*., 409, 144983(2026). https://doi.org/10.1016/j.chemosphere.2026.144983

Dimkpa, C. O. and Bindraban, P. S., Nanofertilizers: New Products for the Industry, *J. Agric. Food Chem*., 66(26), 6462–6473(2017). https://doi.org/10.1021/acs.jafc.7b02150

Food and Agriculture Organization of the United Nations. The State of the World's Forests 2024: Forest-Sector Innovations Towards a More Sustainable Future. Rome: FAO; 2024. https://doi.org/10.4060/cd1211en

Huang, S. and Huang, G., The utilization of quantum dot labeling as a burgeoning technique in the field of biological imaging, *RSC Adv*., 14(29), 20884–20897(2024). https://doi.org/10.1039/D4RA04402A

Iravani, S. and Varma, R. S., Green synthesis, biomedical and biotechnological applications of carbon and graphene quantum dots. A review, *Environ. Chem. Lett.*, 18(3), 703–727(2020). https://doi.org/10.1007/s10311-020-00984-0

Kah, M., Kookana, R. S., Gogos, A. and Bucheli, T. D., A critical evaluation of nano pesticides and nano fertilizers against their conventional analogues, *Nat. Nanotechnol*., 13(8), 677–684(2018). https://doi.org/10.1038/s41565-018-0131-1

Khan, I., Saeed, K. and Khan, I., Nanoparticles: Properties, applications and toxicities, *Arab. J. Chem.*, 12(7), 908–931(2017). https://doi.org/10.1016/j.arabjc.2017.05.011

Khot, L. R., Sankaran, S., Maja, J. M., Ehsani, R. and Schuster, E. W., Applications of nanomaterials in agricultural production and crop protection: A review, *Crop Prot*., 35, 64–70(2012). https://doi.org/10.1016/j.cropro.2012.01.007

Liu, R. and Lal, R., Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions, *Sci. Tot. Environ*., 514, 131–139(2015). https://doi.org/10.1016/j.scitotenv.2015.01.104

Molaei, M. J., Principles, mechanisms, and application of carbon quantum dots in sensors: A review, *Anal. Meth*., 12(10), 1266–1287(2020). https://doi.org/10.1039/C9AY02696G

Raliya, R., Saharan, V., Dimkpa, C. and Biswas, P., Nanofertilizer for Precision and Sustainable Agriculture: Current State and Future Perspectives, *J. Agric. Food Chem.*, 66(26), 6487–6503(2018). https://doi.org/10.1021/acs.jafc.7b02178

Rana, L., Kumar, M., Rajput, J., Kumar, N., Sow, S., Kumar, S., Kumar, A., Singh, S. N., Jha, C. K., Singh, A. K., Ranjan, S., Sahoo, R., Samanta, D., Nath, D., Panday, R. and Raigar, B. L., Nexus between nanotechnology and agricultural production systems: Challenges and future prospects, *Discov. Appl. Sci*., 6, 555(2024). https://doi.org/10.1007/s42452-024-06265-7

Subhash, B., Singh, R., Yadav, D., Rathore, S. S., Raj, R., Avasthe, R., Yadav, S. K., Das, A., Vivek, Y., Yadav, B., Kapila, S., Upadhyay, P. K., Kumar, D. Y. and Singh, V. K., Nanofertilizers for agricultural and environmental sustainability, *Chemosph.*, 292, 133451(2022). https://doi.org/10.1016/j.chemosphere.2021.133451

Tripathi, D. K., Singh, S., Singh, S., Pandey, R., Singh, V. P., Sharma, N. C., Prasad, S. M., Dubey, N. K. and Chauhan, D. K., An overview on manufactured nanoparticles in plants: Uptake, translocation, accumulation and phytotoxicity, *Plant Physiol. Biochem.*, 110, 2–12(2017). https://doi.org/10.1016/j.plaphy.2016.07.030

Verma, K. K., Song, X. P., Degu, H. D., Guo, D. J., Joshi, A., Huang, H. R., Xu, L., Singh, M., Huang, D. L., Rajput, V. D. and Li, Y. R., Recent advances in nitrogen and nano-nitrogen fertilizers for sustainable crop production: A mini-review, *Chem. Bio. Technol. Agric.*, 10, 111(2023). https://doi.org/10.1186/s40538-023-00488-3

Wu, H. and Li, Z., Recent advances in nano-enabled agriculture for improving plant performance, *Crop J.*, 10(1), 1–12(2022). https://doi.org/10.1016/j.cj.2021.06.002