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RESEARCH ARTICLE

Controlled-release nanofertilizer using chitosan nanoparticles loaded with NPK: Development and impact on the yield and nutritional quality of *Solanum tuberosum*

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Abstract
In recent years, nanotechnology has made significant progress in various fields, including agriculture, where nanofertilizers play a pioneering role in improving crop productivity and reducing environmental pollution. In this study, a controlled-release nanofertilizer was developed using chitosan nanoparticles loaded with nitrogen (N), phosphorus (P), and potassium (K). The chitosan nanoparticles (CS-NPs) were prepared via an ionic gelation method using sodium tripolyphosphate and characterized by scanning transmission electron microscopy and infrared spectroscopy. The results revealed that the nanoparticle size ranged from 17.21 nm to 18.32 nm. The controlled release of N, P, and K was evaluated over 240 hours. The nanofertilizer was then applied foliage to *Solanum tuberosum* seedlings under greenhouse conditions. The findings indicated that the 0.25% chitosan nanofertilizer formulation resulted in nanoparticles with relatively high nutrient absorption capacity, with average values of 4.65 mg/L nitrogen, 198.55 mg/L phosphorus, and 1345.27 mg/L potassium. However, the most effective nanofertilizer treatment was the 1% chitosan nanoparticle formulation loaded with 5 ppm N, P, or K, resulting in the best nutritional characteristics among all the fertilization treatments and a 37% increase in the mass yield of *Solanum tuberosum* compared with that of the control. These results suggest that NPK-loaded chitosan nanoparticles could be used as foliar sprays to produce more nutritious and higher-yielding crops.

Keywords: Chitosan nanoparticles; nanofertilizer; *Solanum tuberosum*; agriculture; potato.

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1. Introduction
Potato (*Solanum tuberosum*) is a highly important crop owing to its nutritional content and contribution to the economy and social well-being (Chaudhary et al., 2024). It is widely cultivated across five continents (Mora et al., 2022), making it the third most important food crop globally and providing sustenance for more than 68% of the population (Mali et al., 2023). Owing to its adaptability and extensive worldwide production area, the United Nations has classified potatoes as the fifth most important crop for food security, with an estimated global production of 376 million tons (Devaux et al., 2020).

Among the main potato-producing countries, China and India stand out, accounting for nearly one-third of global potato production in 2020 (Shahbandeh, 2024). In Peru, potatoes are among the main crops in terms of production and consumption, positioning the country as the leading potato producer in Latin America, with a production volume of 6 million tons (Ministerio de Desarrollo Agrario y Riego, 2023). Potatoes are grown in 19 out of 24 regions in the country, with a harvest area reaching 330,790 hectares, and approximately 90% of production is concentrated in the highlands (Instituto Nacional de Estadística e Informática, 2024).

The cultivation of *Solanum tuberosum* is characterized by a high demand for fertilization, particularly potassium and nitrogen, to achieve its potential yield (Berisha et al., 2022). However, this crop has a limited root system, since it has shallow roots which complicate adequate nutrition in the early developmental stages and inevitably leads to increased use of chemical fertilizers to sustain agricultural yields. (Popovic et al., 2025)

Today, agriculture faces significant challenges as the global population rapidly expands, projected in 9 billion people by 2050, which represents a 25% – 70% increase in food demand compared with current level (Nithyaasri et al., 2025). Farmers attempt to address food availability issues and improve yields per hectare in the short term by periodically increasing fertilizer application in fields (Salisu et al., 2024). Consequently, the overall use of fertilizers increased 13-fold between 1950 and 2020, from 15 million to 194 million tons (Jha et al., 2023). In the long term, excessive fertilizer use has significantly reduced soil quality and caused major environmental issues globally, with agriculture being considered the primary source of nitrate, phosphate, and pesticide contamination in water (Ali & Bijay-Singh, 2025). However, conventional fertilizers are naturally limited due to their low nutrient use efficiency, as nutrients bind to the soil in insoluble forms, rendering them inaccessible to plants (Timofeeva et al., 2022). Reports indicate that between 40% and 70% of applied nitrogen is lost to the environment, whereas crops absorb only 10% – 20% of applied phosphorus (Ding et al., 2023). Low nutrient absorption consequently leads to intensified fertilizer use to sustain agricultural crop productivity (Abdel-Hakim et al., 2023).

Therefore, there is significant interest in developing innovative fertilizer systems capable of increasing nutrient absorption efficiency, ensuring better crop productivity, and promoting sustainable agriculture (Goyal et al., 2025). Nanotechnology has emerged as a promising tool for revolutionizing the agricultural industry, as it positively impacts crop productivity and nutritional quality while reducing the harmful effects of agricultural practices on the environment (Bekah et al., 2025). In this context, nanofertilizers have been developed as promising alternatives given the unique properties of nanomaterials (Jha et al., 2024). The application of nanotechnology in agriculture is a highly promising strategy since nutrients encapsulated in nanoparticles possess greater bioavailability and absorption due to their physicochemical and biological properties (Carnero Canales et al., 2025), allowing rapid uptake and penetration into cells within plant tissues, whether applied foliarly or to the soil (Niu et al., 2021).

Nanomaterials stand out for their biodegradable, nontoxic, eco-friendly, and cost-effective characteristics, making them highly suitable for agricultural use and for the development of controlled-release nanofertilizers because of their bioabsorbable and biocompatible nature (Carnero Canales et al., 2024; Prajapati et al., 2022). Additionally, chitosan has been extensively studied and shown to enhance metabolic activities in plants, efficiently transporting active chemical substances across cell membranes.

On the other hand, although chitosan has proven to be a promising material due to its biocompatibility and ability to release nutrients in a controlled manner, there are few studies evaluating its effectiveness as an encapsulating matrix in NPK fertilizer formulations applied to potato crops. This lack of evidence limits the understanding of the agronomic efficiency of these systems in crops essential for food security, preventing us from establishing their true potential to improve crop yield and nutritional quality, as well as their viability as a sustainable alternative to conventional fertilizers (Qin et al., 2025). Therefore, the objective of this study was to evaluate the effects of the controlled-release fertilizer developed with NPK-loaded chitosan nanoparticles (CS-NP@NPK) on yield and nutrition quality of *Solanum tuberosum*.

2. Methodology

Preparation of chitosan nanoparticles

Chitosan nanoparticles were prepared by adapting the ionic gelation method described by Gan et al. (2005). The evaluated chitosan concentrations were set at 0.25% and 1%. Chitosan (80% deacetylation) was dissolved in a 0.35% (w/v) acetic acid (99.7%) solution and allowed to rest for 24 hours to protonate the chitosan. The pH of the solution was adjusted to 5.5. Separately, 0.25% (w/v) sodium tripolyphosphate (TPP, 85%) was dissolved and filtered through Millex® MCE filters (0.22 µm) to remove impurities. Chitosan nanoparticles were prepared by adding 0.25% TPP solution dropwise to the chitosan solution at a 1:1 (v/v) ratio under constant stirring at 900 rpm at room temperature. After all the TPP was added, the mixture was stirred for an additional 60 minutes.

Evaluation of the controlled release of the nanofertilizer

Chitosan nanoparticles were loaded with a saturated 0.35% (w/v) KNO_3 (99%) solution following the procedure of Pourjavadi et al. (2010), as the final released amount indicates the high potential of chitosan as a fertilizer system. Its slow release was evaluated over a 240-hour period. Every 24 hours, 1 mL of the nanofertilizer emulsion was collected and centrifuged for 20 minutes at 10,000 rpm. The N, P, and K contents in the supernatant were measured to determine the slow-release kinetics of the elements (Ha et al., 2019). Total phosphorus was measured via the blue molybdate colorimetric method with a spectrophotometer (Trentman et al., 2021). The total potassium content was determined via atomic absorption spectroscopy (AAS) (Brodowska et al., 2019). The total nitrogen content was determined via the micro Kjeldahl method (Pandey et al., 2022).

Preparation of treatments

For the preparation of the nanofertilizer treatments, the same procedure for preparing the chitosan nanoparticles was followed, but in this case, KNO_3 (pH 5.5) was diluted in the chitosan solution before the addition of TPP. Nitrogen and potassium were sourced from KNO_3, whereas phosphorus was derived from TPP. Three nanofertilizer solutions were prepared at concentrations of 5, 10, and 20 ppm KNO_3.

Characterization of the nanoparticles

The physicochemical properties of the nanoparticles were characterized via dynamic light scattering (DLS) and zeta potential (ZP), which are rapid, simple, reproducible, and noninvasive tools used to measure particle size (hydrodynamic), size distribution, stability in solutions or suspensions, and surface charge during nanomaterial preparation (Bhattacharjee, 2016). Chemical properties are determined via Fourier transform infrared (FTIR) spectroscopy, which is essential for characterizing material structure at the molecular scale (Baudot et al., 2010).

Finally, morphological properties were evaluated via field emission scanning electron microscopy (FE-SEM), a highly versatile technique capable of achieving magnifications exceeding 50,000x, enabling high-resolution imaging for analyzing microstructural characteristics, including the morphological behavior of solid component complex formations (Ramchandani et al., 2023).

Experiment with *Solanum tuberosum* seedlings in a greenhouse

Solanum tuberosum (clones were donated by the Universidad Nacional de San Agustín de Arequipa (UNSA) seedlings of the 'Canchán' variety were planted in black polyethylene bags (15 × 25 cm) (Mamiya et al., 2020). During the experiment, NPK fertilizer was applied weekly from the flowering stage until harvest. Commercial foliar NPK (20--20--20) fertilizer was used as a positive control, whereas chitosan nanoparticles without nutrients served as a negative control. Uniform irrigation ensured similar soil water contents across all the seedlings, maintaining identical growing conditions.

Evaluation of the biophysical characteristics of *Solanum tuberosum* seedlings

Five biophysical characteristics of *Solanum tuberosum* seedlings were evaluated. Plant growth was determined by measuring the height from the soil surface to the top of the plant with a ruler. The leaf area was assessed via ImageJ software. Additional parameters, including the number of leaves, number of tubers, and total weight, were quantified (Perez et al., 2024).

Nutrient analysis

Solanum tuberosum tubers were collected for nutrient content analysis, including proximate analysis (determination of moisture, fat, fiber, ash, soluble carbohydrate, and protein percentages) (Petropoulos et al., 2020). Total phosphorus was measured via the molybdenum blue colorimetric method. The total potassium content was determined via atomic absorption spectroscopy (AAS), and the total nitrogen content was analyzed via the micro Kjeldahl method.

Statistical analysis

Statistical analysis was performed via one-way analysis of variance (ANOVA) and Tukey's test in triplicate via SPSS software. A significance level of $\alpha \leq 0.05$ was considered.

3. Results and discussion

Characteristics of the chitosan-based NPK nanofertilizer

The Fourier transform infrared (FTIR) spectra of the chitosan nanoparticles (Figure 1A and 1B), corresponding to the CS-NPs and CS-NP@NPK, were not significantly different. This similarity is due to the extremely low concentrations of NPK loaded into the nanoparticles, on the order of parts per million, which limits the detection of characteristic signals of NPK components in the FTIR spectrum. Despite the absence of evident changes in the bands, the loading of NPK into the CS-NPs was confirmed through the complementary analyses described in the following sections. On the other hand, the FTIR spectrum shows a peak at 3370 cm^{-1}, attributed to the characteristic O–H stretching bands of chitosan (Mokhtar et al., 2020), as the O–H group exhibits a particularly intense absorption band.

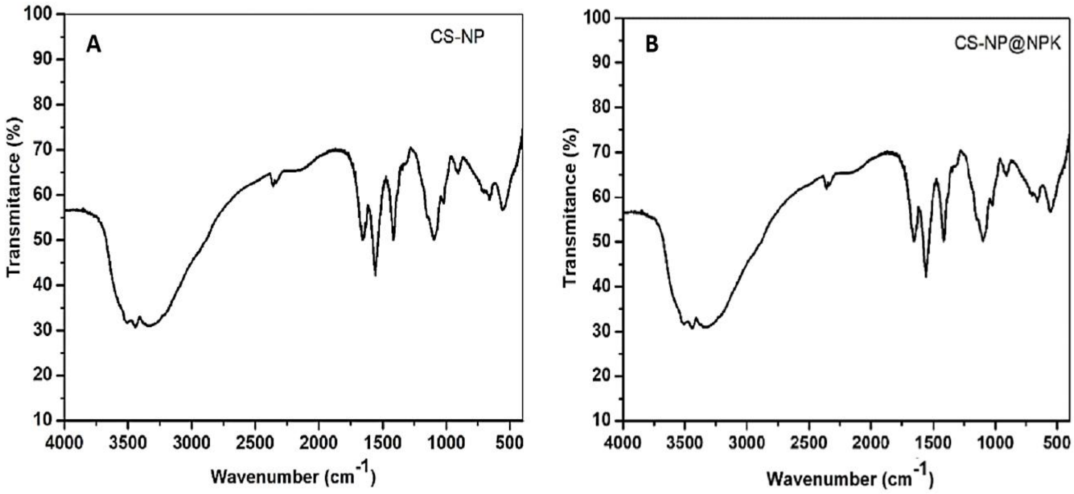

Figure 1. A) FTIR Spectrum of Chitosan Nanoparticles B) FTIR Spectrum of Chitosan Nanoparticles Loaded with NPK.

Concurrently, N–H peaks are observed in the same region, corresponding to the overlap between primary amines and type II amides (Safdar et al., 2019). The peaks at 1600 cm^{-1} and 1380 cm^{-1} correspond to the asymmetric and symmetric bending of the C–H bond, respectively (Flores-Rojas et al., 2020). The additional bands at 1375 cm^{-1}, 1081 cm^{-1}, and 1023 cm^{-1} correspond to C–N stretching, C–O stretching, and O–H bending, respectively, which are characteristic peaks of polysaccharides (Chuc-Gamboa et al., 2019). Another significant absorption band is present at 1220 and 1020 cm^{-1}, representing the free amino group ($-NH_2$) in the C2 position of glucosamine, a distinctive peak of chitosan. With respect to TPP, absorption bands were observed at 1215 cm^{-1}, related to P=O stretching; at 1130 cm^{-1}, corresponding to the symmetric and asymmetric stretching of the $-PO_2$ group; at 1090 cm^{-1}, attributed to the symmetric and asymmetric stretching of the PO_3 group; and at 881 cm^{-1}, associated with the asymmetric stretching of the P–O bond (Silvestro et al., 2020). Moreover, the efficiency and properties of nanoparticle synthesis (morphology and distribution) are strongly dependent on experimental variables such as the chitosan concentration and molecular weight, chitosan/TPP ratio, pH, and stirring time (Benamer Oudih et al., 2023).As a second assay to characterize our nanoparticles and determine the differences between CS-NPs and CS-NP@NPK, analyses of their hydrodynamic size, zeta potential, and particle size distribution (PDI) were performed to confirm the success of encapsulation (Figure 2).

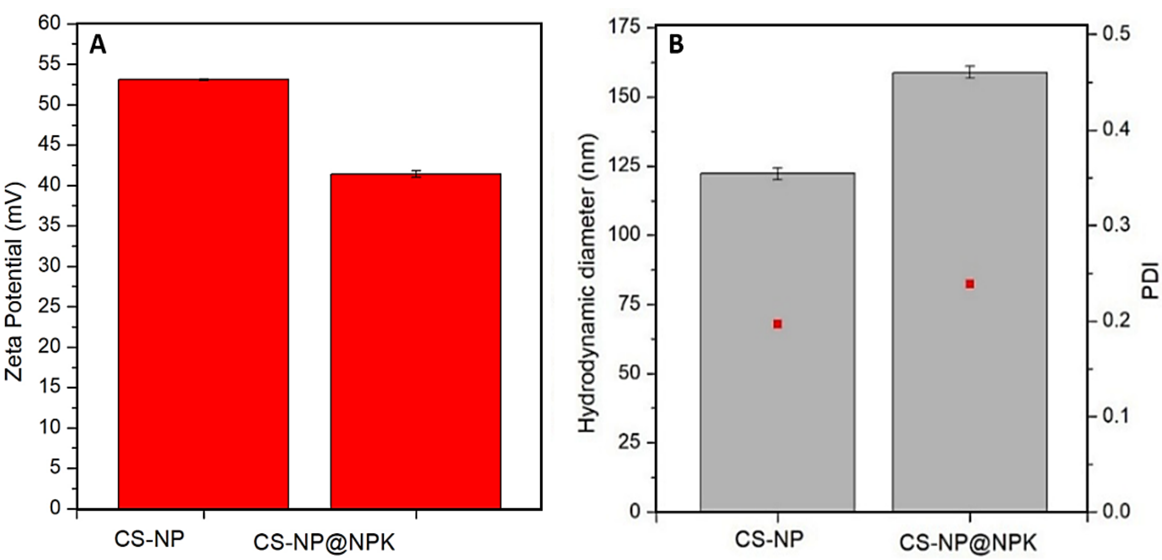

Figure 2. A) Zeta potential comparison of CS-NPs and CS-NP@NPK. B) Hydrodynamic diameter and PDI of CS-NPs and CS-NP@NPK.

In the case of the CS-NPs, the zeta potential was high, remaining above +50 mV, whereas a significant reduction was observed in the CS-NP@NPK, reaching approximately +40 mV. This decrease in zeta potential after NPK incorporation can be attributed to electrostatic interactions between the protonated amino groups of chitosan and the ionic species present in the NPK fertilizer. The presence of anions such as phosphate (PO_4^{3-}) and nitrate (NO_3^-) promotes partial neutralization of the positive charges of chitosan, leading to an overall reduction in the zeta potential. These findings are consistent with previous studies in which the incorporation of ionic species or polyanions reduced the net positive surface charge of chitosan-based matrices. For example, Collado-González et al. (2017) reported similar reductions in the zeta potential when charged biomolecules or compounds were encapsulated within chitosan nanoparticles. Specifically, for fertilizers such as NPK, the ions present form ionic bonds and salt bridges with the protonated amino groups of chitosan, thereby reducing the surface charge of the particles (Xu et al., 2022).

In addition to the change in zeta potential, an increase in hydrodynamic size was observed following NPK encapsulation. The larger average dimension of the CS-NP@NPK than that of the CS-NP suggested that the incorporation of the fertilizer induced an expansion of the chitosan polymeric network or a greater degree of particle aggregation. On the other hand, the slight variation in the PDI indicates a somewhat more heterogeneous size distribution in the NPK-loaded particles. These differences can be explained by the balance of ionic forces and the new intermolecular interactions generated by the presence of salts, which affect the degree of compaction of the polymeric matrix (Motakef Kazemi & Salimi, 2019).

The morphology of the chitosan nanoparticles, characterized via SEM, influenced the nutrient-loading capacity of NPK. Figure 3 shows the results, indicating a spherical surface with a homogeneous and stable size distribution. The average size of the chitosan nanoparticles was 17.21 nm at the 0.25% concentration and 18.32 nm at the 1% concentration. These findings are similar to those reported by Mohammed et al. (2022), who synthesized chitosan nanoparticles via the ionic gelation method and obtained particles ranging from 21 nm to 34 nm in size. These results are smaller than those obtained by Duarte Junior et al. (2017), who applied the polymethylacrylic acid (PMAA) synthesis method and reported nanoparticles in the range of 50–100 nm. These findings are also consistent with those of Bhattacharjee et al. (2023), who used the PMAA method and obtained nanoparticles smaller than 200 nm.

Particle size plays a critical role in nanoparticle properties; therefore, the preference for smaller particles (10 – 50 nm) lies in their advantages over larger particles. As the particle size decreases, the surface area for a given volume (or mass) increases, enhancing coating efficiency, reducing agglomeration, avoiding biological elimination, and improving targeting capabilities (Abbasi et al., 2023).

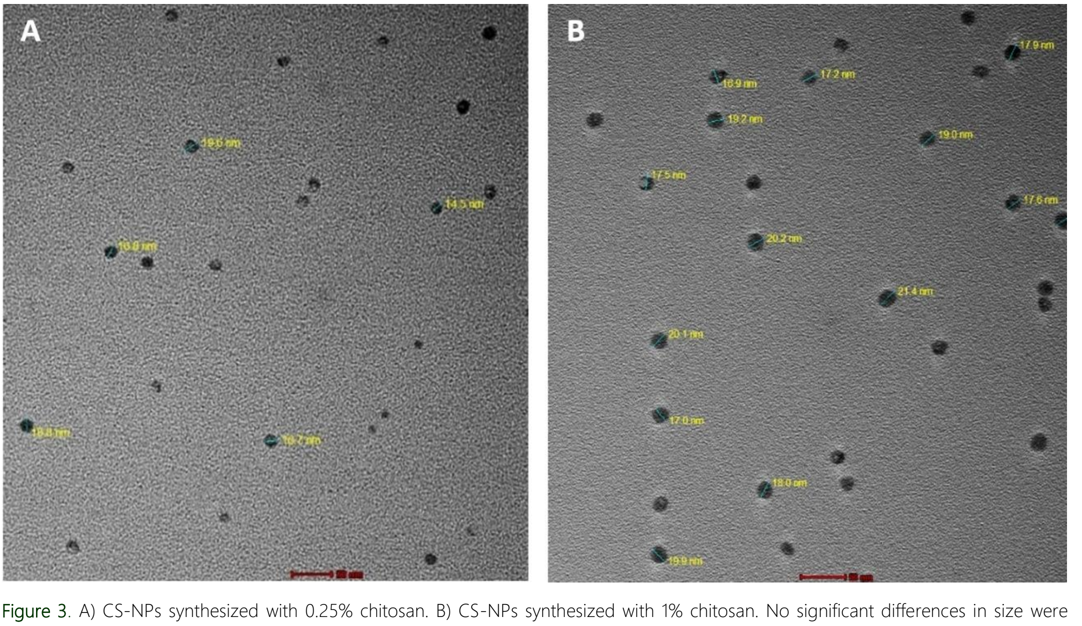

Figure 3. A) CS-NPs synthesized with 0.25% chitosan. B) CS-NPs synthesized with 1% chitosan. No significant differences in size were observed.

Controlled release of the nanofertilizer

The controlled release of the NPK nanofertilizer was analyzed in a solution at pH 5.5. The nutrient release results for N, P, and K from the nanofertilizer are shown in Table 1. This data was used to analyze the nutrient-loading capacity. The results for the 0.25% chitosan nanoparticles indicate nitrogen loading capacities of 0.068%, 0.0065% K_2O, and 0.0055% P_2O_5. For the 1% chitosan nanoparticles, the nitrogen loading capacity was 0.030%, 0.00071% K_2O, and 0.0033% P_2O_5.

As observed, the increasing chitosan concentration decreased the nutrient-loading capacity. This is due to higher levels of ionic crosslinking with TPP, with variations in membrane composition leading to differences in thickness. This is related to density: the denser the membrane components are, the greater their weight and thickness are, increasing their selectivity (Padinjarathil et al., 2023). These results align with those reported by Ha et al. (2019), who achieved increased loading capacity by synthesizing a nanofertilizer with 0.1% chitosan. Their results revealed nitrogen loading capacities of 0.21%, 0.0004% P_2O_5, and 0.116% K_2O. On the other hand, our results for N and P_2O_5 in 0.25% chitosan are equal to or superior to those presented by Corradini et al. (2010), who worked with 0.2% chitosan nanoparticles synthesized with polymethylacrylic acid and used urea, calcium phosphate, and potassium chloride to load NPK into the nanoparticles. They reported a maximum loading capacity of 0.05% for N, 0.04% for K, and 0.006% for P. While their fertilizer had a relatively high potassium-loading capacity, it utilized polymethylacrylic acid, a nonbiodegradable polymer, making it unviable due to its harmful effects on the environment and public health (Bhattacharjee et al., 2023).

Therefore, the 0.25% chitosan nanofertilizer resulted in the nanoparticles with the highest NPK loading in this study, with nitrogen (NO_3^-) standing out as the nutrient with the highest loading capacity. However, it was also the nutrient with the fastest release rate, achieving more than 95% release within the first 96 hours. Despite the potential benefits of nanotechnology in agriculture, nitrogen remains a challenging element to manage for sustained and controlled release. For this reason, modifications to existing nanofertilizer systems are continually being developed to address this challenge (Wang et al., 2023). In this context, Rukchonlatee & Siriphannon (2023) used montmorillonite and chitosan as NPK release matrices and reported that nitrogen was the fastest-releasing nutrient, with 34% released in the first 72 hours. However, this was a more controlled release due to the structure of the montmorillonite nanocomposite, which altered the chitosan structure to slow nutrient release into the medium. Conversely, Cahyaningrum et al. (2024) synthesized a chitosan nanofertilizer via ionic gelation, incorporating calcium ions to enhance charge interactions and release with urea. This resulted in 95.6% urea release within 120 hours. Considering that approximately 46% of urea is nitrogen, the loading capacity was low, and the release was much faster than that of other nanofertilizers. Consequently, we can infer that physically modifying chitosan enhances its mechanical properties, surface area, and adsorption sites, making it a more effective strategy for slowing nutrient release than chemical modification (Keshvardoostchokami et al., 2021).

Table 1
NPK Controlled Release in the Chitosan Nanofertilizer at pH 5.5

Time (h)	Slow release of N, P and K					
	Nitrogen release content (mg/L)		Phosphorus release content (mg/L)		Potassium release content (mg/L)	
	Chitosan (0.25%)	Chitosan (1%)	Chitosan (0.25%)	Chitosan (1%)	Chitosan (0.25%)	Chitosan (1%)
24	20.03±0.80	0.45±0.013	241.07±2.49	101.43±1.16	1284.55±2.62	1215.54±1.46
48	8.39 ±0.30	0.40±0.023	236.03±1.62	98.55±0.09	1276.71±1.85	1249.54±2.03
72	8.81±0.36	0.35±0.058	174.54±2.48	103.58±1.06	1278.61±1.04	1329.86±2.14
96	6.5±0.57	0.30±0.092	186.49±0.70	114.52±0.679	1424.34±1.78	1040.85±1.02
120	0.5±0.081	0.25±0.040	196.64±1.44	101.39±0.89	1487.22±0.985	1019.35±0.64
144	0.45±0.012	0.20±0.008	222.74±1.15	99.94±0.675	1368.76±1.13	975.95±0.99
168	0.4±0.023	0.15±0.014	211.21±1.37	115.96±1.31	1357.24±1.13	1040.96±1.22
192	0.35±0.059	0.10±0.012	172.43±1.45	101.11±1.005	1313.96±0.746	1024.44±1.31
216	0.3±0.092	0.05±0	179.19±1.60	102.36±1.11	1330.79±0.87	978.81±1.00
240	0.25±0.041	0.0±0	169.61±0.92	87.94±0.638	1330.45±0.92	983.97±0.875

With respect to the phosphorus and potassium results, average loading capacities of 198.55 mg/L and 1345.27 mg/L, respectively, were achieved, surpassing the 1% chitosan nanofertilizer loading averages by 49% and 19.3%, respectively. These results can be explained by the fact that higher chitosan concentrations lead to larger nanoparticle sizes and, therefore, a reduced surface area for nutrient loading. This is because intermacromolecular interactions affect the rigidity of the system, impacting the porosity of the polymeric matrix.

On the other hand, the results obtained from the controlled-release evaluation of nitrogen (N), phosphorus (P), and potassium (K) show differential behavior conditioned primarily by two characteristics: the nature of the nutrient and the concentration of chitosan used. This type of behavior has been described in various studies using natural polymer matrices in slow-release fertilization systems (Sharma & Sharma, 2025).

In the case of nitrogen, an accelerated initial release was observed in the 0.25% chitosan nanofertilizer, reaching a maximum concentration of 20.03 mg/L at 24 h. The release then progressively decreases, stabilizing at minimum levels after 120 h. This release pattern can be attributed to the high solubility and mobility of nitrogen, mainly in its ammoniacal or nitric forms, which facilitates its rapid diffusion out of the matrix, thus favoring its loss through volatilization (Sabina et al., 2025). Phosphorus, however, shows less predictable behavior, with sporadic increases over time, especially between 72 and 144 h. This can be explained by the low solubility of phosphorus in aqueous media and its ability to form complexes with the amino and carboxyl groups present in chitosan, causing its release to depend on the gradual swelling or degradation of the chitosan-based matrix (Wujcicki & Kluczka, 2023). Therefore, as chitosan degrades or restructures, previously retained phosphorus can be released at later times, generating the observed peaks.

Potassium release showed more sustained behavior in both nanofertilizer formulations, although greater intensity was observed in the formulation with 0.25% chitosan. Unlike N and P, potassium, being a highly soluble monovalent cation, does not interact significantly with the chitosan matrix, suggesting a release mechanism primarily governed by diffusion (Jamnongkan & Kaewpirom, 2010). Furthermore, previous studies indicate that K retention in polymeric materials is more limited, making its availability more continuous over time.

These results confirm that chitosan concentration is a determining factor in regulating release kinetics, acting as a physical barrier that modulates nutrient release. However, it is also evident that the response of each nutrient is distinct and varies depending on its physicochemical properties, such as solubility, molecular size, and interaction with the matrix (Nandini et al., 2025). Consequently, KNO_3 release can be controlled by altering the polymeric composition of the matrix and modifying the crosslinking time (Perez Bravo & François, 2020). Additionally, the slowest nutrient release was observed for phosphorus loaded into 1% chitosan. Similarly, Ha et al. (2019) reported that phosphorus was the nutrient with the slowest relative release rates, reaching 3% in 240 hours. This result is attributed to the phosphorus content in the NPK nanofertilizer originating from TPP, which is crosslinked with NH_3^+ residues in the chitosan chain.

Effects of NFs on biophysical and nutritional characteristics

The NPK fertilizer was applied to *Solanum tuberosum* seedlings to evaluate its effects on key plant development traits, as shown in Table 2. The results indicate that the T5 treatment resulted in the greatest increase in plant height.

Table 2
Biophysical parameters of *Solanum tuberosum* seedlings

Treatment	leaves		Area of (cm^2)	Number of Sheets	Number of Tubers	Total weight of the tuber (g)
	Nanofertilizer	Height (cm)				
1	Chitosan 1% (5 ppm NPK)	27.2 ± 0.047 f	11.279 ± 1.63 c	97 ± 1.63 f	29 ± 2.06 ef	120 ± 2.05 c
2	Chitosan 1% (10 ppm NPK)	26.2 ± 0.21 ef	11.527 ± 0.33 bc	76 ± 6.16 de	21 ± 2.05 b	203 ± 2.94 e
3	Chitosan 1% (20 ppm NPK)	24.1 ± 0.047 d	8.183 ± 0.16 a	78 ± 3.26 de	29 ± 2.16 ef	200 ± 2.44 e
4	Chitosan 0.25% (5 ppm NPK)	19 ± 0.24 cd	10.471 ± 0.24 ab	69 ± 3.68 cd	31 ± 3.09 f	246 ± 2.44 f
5	Chitosan 0.25% (10 ppm NPK)	27.3 ± 0.047 f	6.876 ± 0.16 a	92 ± 2.94 f	15 ± 1.63 a	121 ±2.16 c
6	Chitosan 0.25% (20 ppm NPK)	20 ± 0.82 b	8.537 ± 0.58 ab	50 ± 4.08 a	23 ± 3.09 bc	140 ± 3.39 d
7	Chitosan 1%	14.6 ± 0.33 a	7.537 ± 0.22 a	63 ± 2.16 bc	22 ± 1.41 b	80 ± 3.77 a
8	Chitosan 0.25%	22.3 ± 0.47 c	10.022 ± 0.081 ab	58 ± 3.09 ab	25 ± 2.49 cd	113 ± 3.26 b
9	Control	25.8 ± 0.081 e	13.696 ± 0.54 c	81 ± 1.69 e	27 ± 1.24 de	83 ± 2.05 a

Values in the same column with different lowercase letters are significantly different according to Tukey's test ($p < 0.05$). The reported values are the means ± standard errors (n = 3).

However, it did not differ significantly from treatments T1 and T2, although it did differ from the remaining treatments. In terms of leaf area, the T1 treatment had the greatest effect but did not significantly differ from the control. In terms of leaf number, T1 again stood out, as it was not significantly different from T5. In terms of the number of tubers, T4 yielded the best result, although it did not differ significantly from those of T3 and T1.

With respect to total tuber weight, T4 again stood out, statistically surpassing all the other treatments and achieving a 163% increase in yield compared with the control. These findings are consistent with the fact that nitrogen is the primary limiting nutrient for *Solanum tuberosum* yield (Errebhi et al., 1998), and both its concentration and timing are major factors in enhancing tuber yield and quality (Haase et al., 2007). As the nitrogen concentration increased, the tuber yields increased. Conversely, low nitrogen doses cause early defoliation and smaller potatoes, as observed in T1, which produced many tubers but of a smaller size. Nitrogen deficiency leads to carbohydrate buildup in leaves, increased carbon allocation to roots, and a relatively high root-to-shoot ratio (Marschner et al., 1996), ultimately reducing yield. Compared with T1, treatments T2 and T3 resulted in a similar number of tubers but resulted in 67% greater yields. In contrast, T4 achieved the highest yield because its 0.25% chitosan concentration provided a greater nutrient-loading capacity, whereas T5 and T6 yielded significantly lower results. Higher nitrogen levels can increase dry matter accumulation in plant parts other than tubers (Goffart et al., 2008).

Phosphorus (P), the second most limiting nutrient in *Solanum tuberosum* cultivation, promotes root growth and accelerates tuber formation, making it critical during early development and tuberization. In this study, TPP was used at a single concentration as the phosphorus source, yielding results similar to those of Dimkpa et al. (2023), who reported that TPP and chitosan increased wheat height by 33% and slightly improved yield by 21%.

Potassium (K) is involved in tuberization and tuber development because the K^+ cation is involved in the catalytic activity of more than 60 plant enzymes, including ATPase and amylosynthase. A constant supply of potassium results in increased starch content in tubers (Sarkar et al., 2010), and starch accumulation directly influences *Solanum tuberosum* biomass and growth. Nevertheless, excess potassium can reduce tuber specific gravity and decrease yield in terms of both number and size. This explains why T5 and T6 resulted in 55% and 46% lower yields, respectively, than did T4 despite having higher N and K loading capacities, whereas T2 and T3 (with the same NPK concentrations) performed better. All NPK nanofertilizer treatments surpassed the control in yield. For T8 and T9, which were based solely on chitosan nanoparticles, the results suggest that low-dose foliar application of high-molecular-weight chitosan enhances *Solanum tuberosum* yield. This significant difference compared with the control aligns with the findings of Steglińska et al. (2024), who reported that chitosan positively affects stem and root growth, gas exchange, and the chlorophyll index in potato plants. Similarly, Falcón-Rodríguez et al. (2017) reported that low-dose foliar application of high-molecular-weight chitosan improved potato yield by 15% – 30%. These effects likely stem from improved nutrient use and enhanced photosynthetic activity, ultimately increasing tuber yields. Another key consideration in *Solanum tuberosum* production is tuber quality, not only in terms of number and weight but also in terms of internal composition. This is closely tied to how different nanofertilizer treatments influence the chemical makeup of tubers (Diana et al., 2024).

As shown in Table 3, treatment T2 presented the highest moisture percentage, which differed significantly from that of all the other treatments, but it also presented the lowest nutritional value.

Table 3
Results of the nutritional analysis of *Solanum tuberosum*

T	Sample	Humidity (%)	Ash (%)	Fat (%)	Protein (%)	Fiber (%)	Carbohydrates (%)	Energy (kcal/100 g)
1	CS 1% (5 ppm NPK)	75.27 ± 0.07 a	1.66 ± 0.17 b	0.12 ± 0.02 bc	4.56 ± 0.30 d	0.46 ± 0.03 e	17.93 ± 0.68 g	91.96 ± 0.91 g
2	CS 1% (10 ppm NPK)	82.31 ± 0.01 f	1.39 ± 0.03 a	0.06 ± 0.04 a	3.95 ± 0.36 a	0.28 ± 0.02 a	12.01 ± 0.47 a	64.76 ± 0.78 a
4	CS 0.25% (5 ppm NPK)	78.49 ± 0.02 d	1.74 ± 0.03 d	0.10 ± 0.04 b	3.94 ± 0.29 a	0.41 ± 0.02 c	15.32 ± 0.50 c	78.76 ± 3.98 c
5	CS 0.25% (10 ppm NPK)	76.12 ± 0.02 b	1.70 ± 0.12 c	0.18 ± 0.02 e	4.36 ± 0.46 c	0.48 ± 0.03 d	17.16 ± 0.80 f	88.66 ± 0.16 f
7	CS 1%	76.22 ± 0.02 b	1.72 ± 0.11 c	0.13 ± 0.02 cd	5.06 ± 0.20 e	0.38 ± 0.02 b	16.49 ± 0.61 e	88.13 ± 1.53 e
8	CS 0.25%	78.91 ± 0.01 e	1.70 ± 0.56 c	0.14 ± 0.008 d	4.05 ± 0.08 b	0.37 ± 0.036 b	14.83 ± 0.61 b	77.52 ± 1.04 b
9	Control	77.31 ± 0.01 c	1.87 ± 0.05 e	0.10 ± 0.004 b	4.59 ± 0.31 d	0.51 ± 0.061 f	15.62 ± 0.57 d	82.76 ± 3.95 d

T: Treatment, CS: Chitosan.

In contrast, the control group had notably higher ash and fiber levels, likely due to the presence of additional trace minerals. The T5 treatment resulted in the highest fat percentage. In terms of protein content, T1 stood out (although not significantly different from the control) and presented a relatively high carbohydrate concentration and energy content, which significantly differed from those of the other treatments. The data from Tables 2 and 3 suggest an inverse relationship between yield and protein content in *Solanum tuberosum* (the key parameter for maintaining this crop). The T4 and T2 treatments, which achieved the highest yields, simultaneously presented the lowest protein percentages. This result can be attributed to the nitrogen demand of the crop at specific growth stages, which influences nitrogen absorption, utilization, and subsequent metabolite synthesis (Abuley et al., 2019). As tubers develop, the available nitrogen content decreases, affecting metabolite production. N uptake through leaves also impacts nutrient transport and distribution, such that leaf biomass and metabolic capacity reflect both yield and quality (Parenteau et al., 2020). Indeed, T4 and T2 presented the greatest leaf areas.

Conversely, although T1 had the lowest yield among the NPK nanofertilizer treatments, it presented the highest protein percentage (with no significant difference from the control).

T1 also increased the yield by 37% compared with that of the control and surpassed that of the control in terms of average carbohydrate content (17.93%), resulting in the highest average energy content. Similarly, Fang et al. (2023) reported that increasing nitrogen reduces potato weight but increases crude protein and ascorbic acid levels. Phosphorus is essential for tuber quality, given its involvement in cell division, starch synthesis, and protein storage (Freeman et al., 1998). Mineral nutrients (particularly nitrogen and potassium) also affect potato lipid composition: nitrogen can lower lipid and phospholipid levels, whereas phosphorus can increase lipid content (Klein et al., 1980). It is therefore unsurprising that T2, which had a lower phosphorus loading capacity and higher nitrogen levels than did T1, presented the lowest fat percentage. Elevated potassium levels are associated with thicker stems, better nutrient transport and water absorption, increased photosynthetic pigments, and improved translocation of photoassimilates. Moreover, potassium enhances enzymatic activity and increases the synthesis and accumulation of soluble sugars, proteins, and starch in tubers, ultimately increasing yield (Shu et al., 2024). In the T7 and T8 treatments, where the chitosan nanoparticles provided nutrients but not supplemental potassium, the yield markedly decreased (Prajapati et al., 2022). Nevertheless, these treatments also resulted in high protein contents, likely due to the role of chitosan as an elicitor and inducer of plant immunity, triggering protein accumulation as part of the plant defense response (Attia et al., 2021). In the absence of potassium, nutrient deficiency stress increases the vulnerability of plants to environmental factors.

Chitosan-induced protection against environmental stress commonly involves the production of reactive oxygen species (ROS) and reactive nitrogen species (RNS) regulated by ROS-scavenging enzymes such as catalase (CAT), superoxide dismutase (SOD), and peroxidases (Divya et al., 2019). However, ROS and RNS also operate as signaling molecules within a finely balanced network, interacting with hormonal pathways that modulate plant growth and development (Yarullina et al., 2023).

As shown in Table 4, the nitrogen percentage was clearly associated with the nutritional quality of *Solanum tuberosum*, especially the protein content, maintaining a direct relationship. The T1 and T5 treatments presented the highest nitrogen percentages and were also the best treatments in terms of nutritional value. In terms of the average nitrogen content in *Solanum tuberosum*, there was a highly significant difference between treatment T1 and other fertilizer treatments. No significant difference was detected between treatments T2 and T4, as they presented the same value; however, both presented highly significant differences from treatments T1 and T5.

Table 4
Results of NPK Compositional Analysis in *Solanum tuberosum*

T	Nitrogen		Phosphorus	Potassium
	Sample	%	mg/100 g	mg/100 g
1	Chitosan 1% (5 ppm)	0.73	323.56	513.55
2	Chitosan 1% (10 ppm)	0.63	180.14	552.34
4	Chitosan 0.25% (5 ppm)	0.63	148.64	533.07
5	Chitosan 0.25% (10 ppm)	0.70	365.88	435.72

T: Treatment.

4. Conclusions

This study developed a controlled release nanofertilizer using chitosan nanoparticles loaded with NPK. Nanoparticle characterization revealed average sizes of 17.21 nm for the 0.25% chitosan concentration and 18.32 nm for the 1% concentration, confirming a homogeneous distribution and spherical morphology suitable for agricultural applications. Chitosan nanoparticles at 0.25% demonstrated a greater nutrient-loading capacity, with values of 0.068% N, 0.0065% K_2O, and 0.0055% P_2O_5. However, increasing the chitosan concentration reduced this capacity because of greater ionic crosslinking with TPP, which affected the thickness and selectivity of the polymeric membrane. Controlled-release tests revealed that nitrogen was released the fastest, with over 95% released within the first 96 h, posing challenges for sustained-release systems. In contrast, phosphorus exhibited the slowest release, likely because of its interaction with chitosan via TPP. Foliar application of the nanofertilizer to *Solanum tuberosum* seedlings significantly improved both their biophysical and nutritional characteristics. Compared with the control, treatment T1 (1% chitosan loaded with 5 ppm NPK) resulted in the highest protein percentage and a 37% increase in tuber mass yield, as well as higher carbohydrate and energy contents. An inverse relationship between yield and tuber protein content was observed, indicating that increased nitrogen absorption during crop development can affect the synthesis of other metabolites. The treatments with relatively high nutrient loads (especially N and K) resulted in relatively high yields but relatively low protein levels. The use of chitosan nanoparticles (CS-NPs) as a controlled nutrient-release system can contribute to more sustainable agriculture by reducing fertilizer application rates and minimizing the environmental impact associated with excessive agrochemical use. Finally, this study underscores the potential of nanotechnology in agriculture and provides a foundation for future research aimed at optimizing nanofertilizer formulations and applications to increase nutrient absorption efficiency and improve the sustainability of agricultural systems.

Credit authorship contribution statement

J. I. Marquez Cazorla: Writing – review & editing, Writing – original draft, Validation, Visualization, Investigation, Conceptualization, Funding acquisition. C. S. Moreno Roque, Writing – original draft, Validation, Investigation, Formal analysis, Funding acquisition. L. P. da Costa: Writing – review & editing, Validation, Methodology, Investigation. C. A. Vera Gonzales: Conceptualization, Investigation, Original draft preparation. C. S. Carnero Canales: Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization, Formal analysis, Supervision.

Declaration of competing interest

All contributing authors declare that they have no conflicts of interest.

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