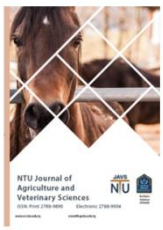
NTU Journal of Agricultural and Veterinary Sciences (2025) 6 (3) : 273-281
DOI: https://doi.org/10.56286/NTU-JAVS.2026.6.3.273-281

IRAQI Academic Scientific Journals

JAVS NTU

P-ISSN: 2788-9890 E-ISSN: 2788-9904
NTU Journal of Agricultural and Veterinary Sciences
Available online at: https://journals.ntu.edu.iq/index.php/NTU-JAVS/index



Influence of Nanoparticle Application and Storage Conditions on Viability, Germination, and Yield of Lettuce (*Lactuca sativa*) Seed.

1st Chinur H. Mahmood[1]
Univ. of Sulaimani, College of Agricultural Engineering Sciences, Horticulture Dept., Kurdistan Region -Iraq.

Article Informations

Received: 16-08- 2025,
Accepted: 23-04-2026,
Published online: 28-09-2025

Corresponding author:
Name: Chinur H. Mahmood
Affiliation : University of Sulaimani, Horticulture Department, College of Agricultural Engineering Sciences
Email:chnwr.mahmud@univsul.edu.iq

Keywords:
Nanoparticle
Germination
Lettuce
Seed

A B S T R A C T

This research analyzes the impact of storage temperature and nanoparticle treatments on the germination, viability, and yield of sativa lettuce seeds. At varying concentrations, lettuce seeds were treated with ZnO, CuO, and TiO2 nanoparticles at 750, 1250, and 1500 mg kg^{-1}, and then stored for six months at 4°C and 10°C. Lab tests were conducted in the College of Agricultural Engineering Sciences from 1st September 2023 in a factorial completely random design (CRD), while the field tests were conducted after the germination of the seeds in the lab, and they were planted in the seed lots after 6 weeks and planted in the field on 15th October 2023 within blocks using the randomize complete block design (RCBD). Observed indicators included some of the most important germination steps, as well as vegetative growth and biochemical indices. Findings indicated that both ZnO @750 mg.kg-1 and CuO @1250 mg.kg-1 nanoparticles enhanced the speed of seed germination, as well as the vigor index and germination rates, when compared to the control. Furthermore, the nanoparticle treatments, especially at 4°C, advanced the head weight, leaf area, and chlorophyll content of the plants' vegetative growth. Chemical composition analysis revealed increased crude protein, carbohydrate, and vitamin content in plants treated with ZnO nanoparticles @ 750 mg.kg-1. Seed production traits, such as average single seed weight and yield per plant, were also positively influenced by specific nanoparticle treatments. These findings demonstrate the potential of nanotechnology to enhance seed viability and crop productivity, contributing to sustainable agricultural practices.

©2026 NTU JOURNAL OF AGRICULTURAL AND VETERINARY SCIENCES, NORTHERN TECHNICAL UNIVERSITY. THIS IS AN OPEN ACCESS ARTICLE UNDER THE CC BY LICENSE: https://creativecommons.org/licenses/by/4.0/
How to Cite: Influence of Nanoparticle Application and Storage Conditions on Viability, Germination, and Yield of Lettuce (Lactuca sativa) Seed. (n.d.). *NTU Journal of Agriculture and Veterinary Science*, *6*(3). https://doi.org/10.56286/NTU-JAVS.2026.6.3.273-281

Introduction

According to [1], the species (*Lactuca sativa*) contains six edible varieties of lettuce: crisphead (iceberg and batavia), romaine, butterhead, leaf, Latin, and stem. All varieties, with the exception of iceberg, have green and red leaf shapes. Different forms gained significance in various locations over time. The predominant kind of romaine lettuce in the Mediterranean region (Spain, Italy, the Middle East, and North Africa) came in a variety of shapes and hues. Butterhead lettuce and the Batavia kind of crisphead lettuce were the most common types in Northern Europe. In Egypt, the Middle East, and China, stem lettuces continued to be significant. During the early 1900s, all varieties of lettuce were consumed in the United States, although butterhead, leaf, and American Batavia varieties were the most popular. Tennis Ball Black Seeded (butterhead), "Big Boston" (butterhead), "Hanson" (Batavia), and "Prizehead" (red leaf) were the top lettuce varieties [2].

Storage temperature and NPs (nanoparticles) have an effect on seed viability and crop yield in agriculture, particularly in lettuce production. Storage temperature also greatly impacts a seed's longevity and its ability to germinate over a period of time [3]. The unique physical and chemical traits of nanoparticles allow for a positive increase in the rate of sprout germination, the level of stress resistance, and nutrient assimilation by the plants [4]. The application of nanoparticles in the agricultural industry has increased in the last few years due to their potential to sustainably increase crop yields [5]. Some research claims that various nanoparticles such as SiO_2, Ag, and ZnO have been reported to enhance the physiological and enzymatic activities of seedlings, which promote greater plant growth and germination speed [6]. Such nanomaterials are beneficial for enhancing agricultural productivity in tough climatic conditions because they are able to mitigate the adverse effects of high temperature and environmental stress [7]. Even so, seed quality is best maintained when temperature-controlled storage is employed. Excessively high temperature can harm the seeds by accelerating the aging through oxidative enzyme activity and enhancing peroxidation of lipids and membranes; cold temperatures cause physical damage to the tissues of the seed [8]. If done correctly, manipulating the storage temperature and adding other elements such as NPS may prove beneficial in seed handling and ultimately productivity in agriculture [9]. This particular study is aimed at determining the impact of thermal and nanomaterials on the viability of lettuce seeds together with the prospective crop yield. It will also address the physiological and biochemical mechanisms where nanotechnology enhances seed thermotolerance and how these technologies could help create greener agricultural practices.

Materials and Methods

The study involves (*Lactuca Sativa* L. Var. Longifolia Cv. Marul) seeds of the iceberg type by using a factorial (CRD) design for the laboratory and germination stage. Seeds are dry-dressed with each of the synthesized nanoparticles, viz., ZnO, CuO and Tio2 @ 750, 1250, and 1500 mg kg^{-1} in screw-capped glass bottles at room temperature. The glass bottles containing seeds and nanoparticles were manually shaken gently for 3 min., 5 times in a span of 3 h [5]. Seeds shaken without nanoparticles served as a control. After dry dressing with the nanoparticles, the seeds were packed in cloth bags and stored under ambient conditions (4 and 10 ± 1°C temperature and 95 ± 3% RH) for 6 months, starting on 1st March 2023, with three replicates. The seeds started to test germination for each treatment separately from 1st September 2023 and were planted in the seed lots after 6 weeks and planted in the field on 15th October 2023 by using RCBD with 3 replicates. In this case, the three different nanoparticles, two-degree temperatures, and six-month rest period are listed below in Table (1):

Table 1. Treatments of the experiment

Vegetables	Treatments
Lettuce	T0: 4 °C for 6 months
	T1: 10 °C for 6 months
	T2: ZnO @ 750 mg.kg^{-1} nanoparticles and stored at 4 °C for 6 months
	T3: ZnO @ 750 mg.kg^{-1} nanoparticles and stored at 10 °C for 6 months
	T4: CuO @ 1250 mg.kg^{-1} nanoparticles and stored at 4 °C for 6 months
	T5: CuO @ 1250 mg.kg^{-1} nanoparticles and stored at 10 °C for 6 months
	T6: TiO_2 @ 1500 mg.kg^{-1} nanoparticles and stored at 4 °C for 6 months
	T7: TiO_2 1500 mg.kg^{-1} nanoparticles and stored at 10 °C for 6 months

Parameters calculated:

Seed germination parameters: for each replicate and treatment, 50 seeds were tested in a Petri dish, and these equations was taken:

Germination Percentage (G.P %), Germination Index (G.I), Mean Germination Time (M.G.T(day)), Mean Daily Germination (M.D.G (seed.day^{-1})), Time to 50% G.(days), Germination Speed (G.S(seed.day^{-1})), Germination Rate Index (G.R.I.).

Vegetative growth and yield characteristics: These data for each replicate and treatment were taken for 10 plants:

Head weight (g), Head length (cm), Head diameter (cm), Leaf area (cm^2), Number of leaves per plant, Stem diameter (cm), Days to head formation, Days to maturity from planting, Yield per plant (g) (main head and side shoot), yield per hectare (tons.ha^{-1}).

Chemical components: These data for each replicate and treatment were taken for 100 g fresh weight:

Dry matter%, Crude protein (%), Crude fiber (%), Carbohydrates (%), Crude fat (%) and Ash content (%), pH level, Total soluble solids (TSS) (Brix) and Titrable acidity%

Vitamins: These data for each replicate and treatment were taken for 100 g fresh weight:

Vitamin C (mg), Vitamin A (µg RAE) and Vitamin K (µg).

Minerals and other components: these data for each replicate and treatments were taken for 100 g fresh weight:

Calcium (Ca)(mg), Iron (Fe)(mg), Potassium (K)(mg), Magnesium (Mg)(mg), Phosphorus (P)(mg), Glucosinolates (µmol.g^{-1}), Nitrates(mg.kg^{-1})

Seed production traits : these data for each replicate and treatment were taken for 10 plants:

Weight of a single seed (mg), weight of 1000 seeds (g) and seed yield per plant (g).

Statistical analysis:

The Factorial—CRD for the laboratory part and RCBD in the field—was used in this study. The statistical analysis system XL-State (2019) program was used to analyze the data obtained from the study. Duncan's multiple range test was used to determine significant differences among means within the factor on all studied traits.

Results

Germination response:

For lettuce, the data in table (2) for each of Germination Percentage (G%), Germination Index (G.I) Mean Daily Germination (M.D.G), and Time to 50% Germination showed that there was numerical differences recorded between treatments but showed no significant differences.

For Mean Germination Time (M.G.T), T7 had the longest germination time by (17.23), significantly bypass the others and (T5) had the shortest, indicating faster seed sprouting by (15.14). For Germination Speed (G.S), (T3) had the maximum Germination Speed, indicating that seeds germinated more quickly under this treatment which gave (4.07 seed.day^{-1}) which significantly exceed the others and (T7) had the minimum Germination Speed, meaning the germination process was slower compared to other treatments and recorded (2.80 seed.day-1).

However, the lack of statistical significance in this study could be due to the seed's intrinsic characteristics and environmental adaptability.

When calculated Germination Rate Index (GRI), (T7) had the maximum Germination Rate Index, meaning it had the fastest overall germination process by (17.23) superior significantly to (T5) which had the minimum Germination Rate Index, indicating slower overall seed germination under this temperature by (15.14).

Plant and yield traits:

These results in figure (1) highlight how nanoparticle treatments and temperature adjustments significantly impact the growth and yield of lettuce.

The number of leaves before head formation, leaf area (cm²) and leaf length (cm) recorded numerical differences but not significantly enough to be mentioned.

For head fresh weight (g), data denotes that (T3) recorded (797.62 gm) as the heaviest lettuce heads show enhanced growth and biomass accumulation and significantly outstripping the others and (T1) produced the lightest lettuce heads, suggesting restricted growth by (383.02).

Table 2. Germination Response of Lettuce seeds to Treated with Some Nanoparticles and Storage In Different Temperature Regime.

Vegetable	Treatments	G.P %	G.I	M.G.T (day)	M.D.G (seed.day^{-1})	Time to 50% G. (days)	G.S (seed.day^{-1})	G.R.I.
Lettuce	T0	100 a	22.40 a	16.55 abc	4.11 a	2.87 a	3.98 ab	16.55 abc
	T1	100 a	26.48 a	17.01 ab	4.34 a	2.68 a	3.89 ab	17.01 ab
	T2	100 a	23.12 a	16.24 abc	3.72 a	2.37 a	3.38 ab	16.25 abc
	T3	100 a	25.68 a	15.85 abc	4.44 a	2.83 a	4.07 a	15.85 abc
	T4	100 a	26.85 a	17.16 ab	3.837 a	2.410 a	3.120 ab	17.163 ab
	T5	100 a	21.61 a	15.14 c	4.10 a	2.90 a	3.89 ab	15.14 c
	T6	100 a	21.30 a	15.47 bc	3.76 a	3.00 a	3.36 ab	15.47 bc
	T7	100 a	24.11 a	17.23 a	3.46 a	2.30 a	2.80 b	17.23 a

Means having different small letters (abc) in the same trait are significantly different ($p \leq 0.05$).

Longest leaves which could contribute to higher photosynthesis efficiency recorded by (T2) with the average (24.66 cm) significantly bypass the others (T3) had the shortest leaves, which might have limited light absorption which have the average (21.96).

Leaf width (cm) in (T2) had the widest leaves (8.33 cm), which may indicate improved plant vigor this significantly overcome the others and recorded (5.59) the narrowest leaves and poorer leaf expansion in (T0) plants.

Widest Head Diameter (cm) enhanced head development recorded (15.66 cm) by (T2) surpass significantly the others and given (11.02) in plants of (T1).

Chlorophyll Content (SPAD Value) is greater in (T2) and recorded (46.00 spad) significantly bypass the others and recorded (34.93) in (T0) plants as a minimum chlorophyll content, which may have limited plant growth.

Days to Head Formation (days) took a longest time to form heads (78.85 days), indicating slow growth by (T0) plants but (T2) had the fastest head formation and rapid development under this treatment and given (61.66).

The longest time to reach maturity, or days to maturity, was (93.18 days) by plants of (T0) but (T2) surpassed the plant of it by recording (75.33) and matured fastest, showing accelerated growth and productivity.

Maximum plant yield (g) confirming the effectiveness of this treatment in enhancing plant biomass, was (797.62 g) in (T3) its significantly bypassed the others by (383.02) as the minimum plant yield, indicating reduced productivity by (T1).

Maximum Yield per Hectare (tons.ha^{-1}) obtained by (T3) and recorded (31.90 tons) reflecting greater productivity which is predominantly surpass the others and recorded minimum yield per hectare (15.32) by (T1) confirming its lower efficiency in enhancing crop output. Table (3) provides a comprehensive analysis of

Chemical Composition of Lettuce Heads

the chemical composition of lettuce heads grown from seeds treated with nanoparticles and subjected to different temperature regimes (T0 to T7). The measured characteristics include dry matter content (%), crude protein (%), crude fiber (%), carbohydrates (%), lipids (%), ash content (%), vitamin C (mg), vitamin A (µg RAE), vitamin K (µg), calcium (Ca) (mg), iron (Fe) (mg), potassium (K) (mg), magnesium (Mg) (mg), phosphorus (P) (mg), nitrates (mg.kg^{-1}), pH level, total soluble solids (TSS) (Brix), and titrable acidity (%).

For dry matter content (%), (T5) with a value of 8.193%, had the maximum value, significantly surpass the others and (T0) gave (4.750%) which had the minimum value.

Crude protein (%) peaked in (T2) by (1.943%) and was significantly minimum in (T1) about (0.370%).

While crude fiber (%) was maximum in (T4), reaching (2.827%) and significantly recorded minimum in (T0) by (0.723%).

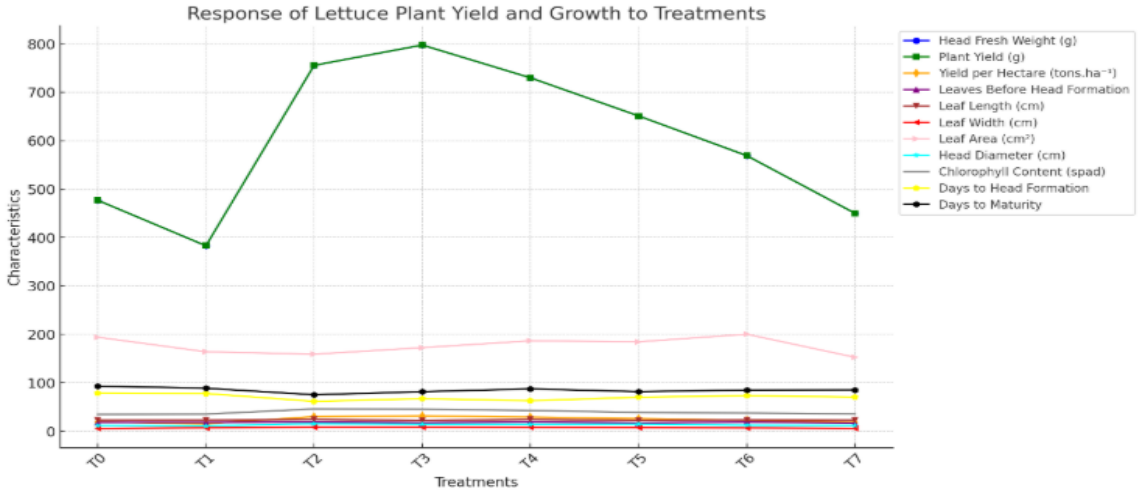
Carbohydrates **(%)** and lipids (%) were maximized in (T3) by (3.710% and 1.483%, respectively), significantly bypassing the others and (T0) showing the minimum values.

About Carbohydrates (%) we noticed that (T3) gave (3.710%) also had the maximum carbohydrate content, this significantly overcame the others, and (T0) recorded (2.083%) as a minimum value. This shows that (T3) is the most effective treatment for boosting sugar and fiber levels in lettuce.

Data for Lipids (%) recorded the maximum percentage in (T3) by (1.483%) had the maximum fat content significantly exceed the others and , (T0) gave

(0.143%). This indicates that T3 is the most effective treatment for increasing lipid content in lettuce.

For Ash Content (%), (T2) recorded (1.713%) had the maximum mineral content, while T0 (0.407%) had the minimum. This suggests that T2 is the most effective treatment for enhancing the mineral profile of lettuce.



For pH level, data revealed that the treatment (T4) marked (6.50) had the maximum pH level this significantly marked down and recorded (5.18) by (T0). Related to Total Soluble Solids (TSS) (Brix) the treatment (T4) gave (5.50 Brix) as a maximum TSS, indicating the maximum concentration of sugars, minerals, and other soluble solids in the lettuce, and this significantly superior to the othertreatment (T6) which recorded (4.08 Brix) as a minimum TSS, suggesting a lower concentration of soluble solids and potentially less sweetness or flavor.

Data about Titrable Acidity (%) explains that the treatments recorded numerical differences but these differences were not significantly.

Data recorded about Vitamin C (mg) denote that (T3) gave (24.04 mg) had the maximum Vitamin C content and significantly exceeded the others and (T1) gave (16.39 mg) had the minimum value, his suggests that (T3) is the most effective treatment for enhancing the antioxidant properties of lettuce.

For Vitamin A (µg RAE) the maximum value recorded by (T2) about (245.00 µg RAE) had the maximum Vitamin A content significantly bypass the others and (T1) gave (178.82 µg RAE) as a minimum value. This indicates that (T2) is the most effective treatment for boosting pro vitamin A carotenoids in lettuce.

The same table denote that Vitamin K (µg) reached the significant maximum value for (T1) by (164.08 µg) had the maximum Vitamin K content, while the minimum was in (T0) by (108.05 µg) had the minimum. This shows that (T1) is the most effective treatment for increasing Vitamin K levels in lettuce.

Calcium (Ca) (mg), data showed that the treatments recorded numerical differences between them but these differences was not significantly.

For Iron (Fe) (mg) the maximum significant value by (T2) about (1.86 mg) and the minimum was by (T0) and gave the value (0.65 mg), his indicates that T2 is the most effective treatment for boosting iron levels in lettuce.

Potassium (K) recorded the maximum content in (T2) by (250.69 mg) which this significantly superior to (T0) and gave the value (175.10 mg), this shows that T2 is the most effective treatment for increasing potassium levels in lettuce.

Data belongs to Magnesium (Mg) shows that the treatment (T2) recorded (19.97 mg) had the maximum magnesium content, while T0 (10.44 mg) had the minimum. Magnesium is essential for muscle function, nerve signaling, and bone health, so T2 is the most effective treatment for enhancing this mineral in lettuce.

For Phosphorus (P),(T5) gave (26.85 mg) recorded the maximum phosphorus content, significantly exceeding other treatments, and for (T0) recorded (16.37 mg) had the minimum value.

Content of the heads in nitrates ($mg.kg^{-1}$) clair that Treatment (T0) gave (2398.15 $mg.kg^{-1}$) as a maximum nitrate content, this significantly bypass the others exactly (T3) which recorded (747.82 $mg.kg^{-1}$) the minimum.

Seed production traits:

The table (4) provides data on seed production traits for lettuce under different treatments (T0 to T7) involving nanoparticles and temperature regimes. The traits measured are weight of a single seed (mg), weight of

1000 seeds (g), and seed yield per plant (g), we explained these results as follows:

For Lettuce, (T2) resulted in the maximum average single seed weight (1.69 mg) and weight of 1000 seeds (1.69 g), while (T3) achieved the maximum seed yield per plant (3.60 g) which significantly transcends the others, and gave the minimum values across all parameters were in (T0), with a average single seed weight of (0.56 mg), weight of 1000 seeds of (0.56 g), and seed yield per plant of (1.26 g).

Table 3. Lettuce head chemical content produced from seeds treated with some Nanoparticles and different temperature regimes

characteristics	Treatments							
	T0	T1	T2	T3	T4	T5	T6	T7
Dry matter content (%)	4.750 b	4.783 b	8.117 a	7.743 a	7.700 a	8.193 a	6.040 b	5.553 b
Crude protein (%)	0.597 b	0.370 b	1.943 a	1.820 a	1.743 a	1.480 a	1.443 a	0.860 b
Crude fiber (%)	0.723 d	0.747 d	2.790 a	2.680 ab	2.827 a	2.410 ab	2.123 bc	1.687 c
Carbohydrates (%)	2.083 c	2.117 bc	3.603 a	3.710 a	3.597 a	2.920 abc	3.060 ab	2.507 bc
Lipid (%)	0.143 c	0.200 c	0.800 abc	1.483 a	1.140 ab	1.000 ab	0.697 bc	0.663 bc
Ash content (%)	0.407 c	0.640 c	1.713 a	1.567 a	1.423 ab	1.293 ab	1.387 ab	0.913 bc
pH level	5.18 c	5.27 c	6.45 a	6.48 a	6.50 a	6.44 ab	6.36 ab	6.18 b
Total soluble solids (TSS) (Brix)	4.18 b	4.15 b	5.32 a	5.15 a	5.50 a	4.57 b	4.08 b	4.18 b
Titrable acidity%	0.12 a	0.16 a	0.12 a	0.13 a	0.14 a	0.11 a	0.13 a	0.15 a
Vitamin C (mg)	16.89 c	16.39 c	22.34 a	24.04 a	21.47 ab	21.42 ab	21.26 ab	18.87 bc
Vitamin A (µg RAE)	192.83 de	178.82 e	245.00 a	240.96 ab	235.92 ab	220.31 bc	227.15 ab	202.42 cd
Vitamin K (µg)	108.05 d	164.08 a	131.56 bc	148.52 ab	138.26 bc	120.85 cd	130.15bcd	121.09 cd
Calcium (Ca) (mg)	26.56 a	23.80 a	29.49 a	26.42 a	29.66 a	26.81 a	23.95 a	30.11 a
Iron (Fe) (mg)	0.65 c	0.68 c	1.86 a	1.52 ab	1.30 abc	1.79 ab	1.07 bc	1.74 ab
Potassium (K) (mg)	175.10 c	230.88abc	250.69 a	247.25 a	237.87 ab	211.49 abc	182.02 bc	198.85 abc
Magnesium (Mg) (mg)	10.44 c	11.20 c	19.97 a	18.37 ab	14.12 bc	16.34 ab	11.66 c	14.36 bc
Phosphorus (P) (mg)	16.37 c	17.20 bc	20.91 abc	24.31 abc	25.07 abc	26.85 a	25.83 ab	25.37 abc
Nitrates (mg.kg^{-1})	2398.15 a	1808.63ab	847.57 c	747.82 c	902.12 c	838.86 c	912.06 c	1028.27 bc

Means having different small letters (abc) in the same trait are significantly different ($p \leq 0.05$).

Table 4. Seed production traits of lettuce produced from seeds treated with some Nanoparticles and different temperature regimes

Vegetable	Treatments	weight of single seed (mg)	weight of 1000 seeds (g)	Seed yield per plant (g)
Lettuce	T0	0.56 b	0.56 b	1.26 e
	T1	1.60 a	1.60 a	2.10 cd
	T2	1.69 a	1.69 a	3.43 a
	T3	1.58 a	1.58 a	3.60 ab
	T4	1.48 a	1.48 a	3.36 ab
	T5	1.48 a	1.48 a	2.37 cd
	T6	1.47 a	1.47 a	2.73 bc
	T7	1.48 a	1.48 a	2.00 d

Means having different small letters (abc) in the same trait are significantly different ($p \leq 0.05$).

Discussion

Germination response:

Germination Response of Lettuce Seeds to Nanoparticle Treatments and Temperature Regimes

The germination parameters observed indicate that nanoparticle treatments and storage temperature regimes influenced lettuce seed performance. Mean Germination Time (MGT) was longest in T7 (17.23 days), which suggests a delayed germination response, potentially due to unfavorable storage conditions affecting enzymatic activity and seed metabolism [10]. On the contrary, T5 showed shortest MGT (15.14 days), which may suggest the ideal conditions for seed soaking and metabolic processes during the breaking of dormancy [11].

GS was also the best in T3 (4.07 seed.day^{-1}), which is expected because of the higher seed vigor associated with the seed's enhanced hydroponic and stress-mitigation capabilities because of the particles

[12]. Nanoparticles increase germination by enhancing water absorption and raising enzyme activities [13, 14]. On the other hand, T7 displayed the lowest GS (2.80 seed.day^{-1}) portraying less efficient germination. GRI also revealed the same trend, where T7 had the highest GRI value (17.23) compared to T5 at the lowest (15.14), confirming that temperature conditions are important in determining the speed of germination [15]. Germination rate was highest in T5 (0.29) and lowest in T7 (0.24). This correlates with other research which explains how nanoparticles can improve the cellular processes associated with germination. [16] found that nanoparticles led to more uniform seedlings emerging due to the germination process being enhanced on a cellular level, while [6] improved nanoparticle stem seed membrane permeability, aiding in the crucial stages of germination. The Vigor Index (VI) T5 was highest (2433.33) therefore supporting the hypothesis that nanoparticles improve seedling vigor and growth [17].

Plant and yield traits:

The quantitative distinctions observed with respect to the characteristics of the leaves—range in their length, area, and the number of leaves—were there but not of significance, which is an indication that there are additional factors other than the nanoparticles and temperature that contribute to growth [18].

The freshest weight of the head was at its peak for the (T3) group with (797.62 g), which can be assumed to be a result of great improvement for biomass accumulation as a result of proficient photosynthetic activity along with increased nutrient absorption [19]. The first treatment group recorded the least fresh weight (383.02 g) which is attributed to impaired seed storage conditions that are suboptimal. (T2) registered the longest leaves in comparison to other treatments with (24.66 cm). (T2) could also yield higher figures for photosynthetic productivity, ratifying the notion that leaf expansion improves light capture and carbon assimilation [20]. In (T2) the leaf width was wide at 8.33 cm, which, paired with the better plant recovery indicates most liked over the former treatment.

In (T2), the highest value for head formation (T2) came with an average of 15.66 cm, so they possess the most recommendable criterion on head measurements, which could have been the result of superior cellular expansion and division due to nanoparticle treatments [21]. (Singh *et al*., 2021). Moreover, the highest value of chlorophyll content was registered at 46.00 SPAD, which pointed to an increase in photosynthesis and possible crop yield improvement [22]. In addition, the most favorable value for the average time taken to achieve head formation was also recorded in (T2) with a value of (61.66 days), which to some degree suggests that the use of nanoparticles enhanced the rate of development, possibly by affecting the signaling pathways of hormones [23]. Furthermore, T2 was also the most advanced treatment for the average number of days taken to reach maturity, with a value of 75.33 days, which validates higher yields.

On the contrary, the most productive yield per hectare was reached in (T3), with an average of (31.90 tons/ha), which illustrates a bigger productivity as a result of the positive effects of nanoparticles on taking up nutrients and biomass production [24]. On the other hand, T1 reported the least average yield at 15.32 tons/ha^{-1}, while the remaining treatments showed an increased productivity, further illustrating the detrimental impact of poor environmental conditions on the lettuce productivity.

Chemical Composition of Lettuce Heads

The content of dry matter was greatest in T5 (8.193%), which indicates a more efficient biomass production and cell wall development, which is consistent with the literature on plant growth enhancement through nanoparticles [25]. Crude protein content was highest in T2 (1.943%), which indicates improved nitrogen use, whereas T1 had the lowest value (0.370%) which is in line with evidence that temperature stress is detrimental to protein synthesis [26].

The greatest amounts of carbohydrates and lipids were in T3 (3.710% and 1.483%), respectively, thereby indicating increased metabolic processes and nutrient remobilization. This corroborates previous reports of nanoparticles' effects on plant biochemistry [27]. Ash content (T2) had the highest amount of ash content (1.713%), which implies higher mineral content, which is important for plant development and human health. Vitamin C, on the other hand, was maximized in T3 (24.04 mg), which indicates the possibility that nanoparticles increase antioxidant accumulation [28].

The greatest amount of iron, ,potassium and magnesium was in (T2), which reinforced the hypothesis that nanoparticles enhance micronutrient uptake and translocation [29]. The greatest amount of phosphorus was observed in T5 (26.85 mg) which

confirms its positive effect on phosphorus metabolism. The highest nitrate content was T0 (2398.15 mg kg^{-1}), which suggests lower nitrogen assimilation efficiency under such conditions.

Seed production traits:

For lettuce, T2 gives the highest average single seed weight (1.69 mg) and weight of 1000 seeds (1.69 g), which is due to improved seed quality, consistent with other studies on nanoparticle-enhanced seed vigor [30]. Seed yield per plant was highest in T3 (3.60 g), indicating improved reproductive efficiency, potentially reflected in nanoparticle-induced stress tolerance [31].

Conclusion

The results indicate that treating lettuce seeds with nanoparticles—particularly ZnO @750 $mg.kg^{-1}$ and CuO @1250$mg.kg^{-1}$ combined with storage at 4°C significantly enhanced germination, vegetative growth, and yield.

ZnO @ 750 $mg.kg^{-1}$ treatment at 4°C showed superior improvements in protein, carbohydrate, and micronutrient content, reflecting enhanced crop quality. Nanoparticle applications accelerated maturation and increased both quantitative and qualitative productivity. These findings underscore the potential of nanotechnology as a tool for improving seed performance and promoting sustainable agriculture.

References

1. Ryder, E. J. (1999). *Lettuce, endive and chicory*. CABI Publishing, Wallingford, UK.
2. Wei, T., Van Treuren, R., Liu, X., Zhang, Z., Chen, J., Liu, Y., ... and Liu, H. (2021). Whole-genome resequencing of 445 *Lactuca* accessions reveals the domestication history of cultivated lettuce. *Nature Genetics*, 53(5), 752–760.
3. Finch-Savage, B. (2013). *Seeds: Physiology of development, germination and dormancy – JD Bewley, KJ Bradford, HWM Hilhorst, H. Nonogaki. 392 pp. Springer, New York–Heidelberg–Dordrecht–London, 2013. ISBN 978-1-4614-4692-7. Seed Science Research*, 23(4), 289.
4. Farooq, M. A., Hannan, F., Islam, F., Ayyaz, A., Zhang, N., Chen, W., and Zhou, W. (2022). The potential of nanomaterials for sustainable modern agriculture: Present findings and future perspectives. *Environmental Science: Nano*, 9(6), 1926–1951.
5. Ahmed, G. O., Halshoy, H. S., and Mahmood, C. H. (2024). Titanium nanoparticle and humic acid applications improve seed germination, growth development, and phytochemical contents of lettuce (*Lactuca sativa*) plants. *BioNanoScience*, 14, 4930–4941. https://doi.org/10.1007/s12668-024-01545-3
6. Mahakham, W., Theerakulpisut, P., Maensiri, S., Phumying, S., and Sarmah, A. K. (2017). Nanopriming technology for enhancing germination and starch metabolism of aged rice seeds using phytosynthesized silver nanoparticles. *Scientific Reports*, 7(1), 8263. https://doi.org/10.1038/s41598-017-09074-2
7. Rai, P. K., Lee, S. S., Zhang, M., Tsang, Y. F., and Kim, K. H. (2018). Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International*, 125, 365–385. https://doi.org/10.1016/j.envint.2018.03.067
8. Walters, C., Wheeler, L. J., and Grotenhuis, J. M. (2005). Longevity of seeds stored in a genebank: Species characteristics. *Seed Science Research*, 15(1), 1–20. https://doi.org/10.1079/SSR2004195
9. Shelar, A., Nile, S. H., Singh, A. V., Rothenstein, D., Bill, J., Xiao, J., ... and Patil, R. (2023). Recent advances in nano-enabled seed treatment strategies for sustainable agriculture: Challenges, risk assessment, and future perspectives. *Nano-Micro Letters*, 15(1), 54.
10. Bewley, J. D., Bradford, K. J., Hilhorst, H. W. M., and Nonogaki, H. (2013). *Seeds: Physiology of development, germination and dormancy*. Springer.
11. Nautiyal, P. C., Sivasubramaniam, K., and Dadlani, M. (2023). Seed dormancy and regulation of germination. *Seed Science and Technology*, 52, 39–66.
12. Santás-Miguel, V., Arias-Estévez, M., Rodríguez-Seijo, A., and Arenas-Lago, D. (2023). Use of metal nanoparticles in agriculture: A review on the effects on plant germination. *Environmental Pollution*, 334, 122222.
13. Rico, C. M., Majumdar, S., Duarte-Gardea, M., Peralta-Videa, J. R., and Gardea-Torresdey, J. L. (2011). Interaction of nanoparticles with edible plants and their possible implications in the food chain. *Journal of Agricultural and Food Chemistry*, 59(8), 3485–3498.
14. Landa, P., Burketová, L., and Kvíčala, J. (2019). Nanoparticles as a tool for plant improvement. *Scientific Reports*, 9(1), 6515.
15. Finch-Savage, W. E., and Bassel, G. W. (2016). Seed vigour and crop establishment: Extending performance beyond adaptation. *Journal of Experimental Botany*, 67(3), 567–591.
16. Jalali, M., Zafari, D., and Tavassoli, A. (2018). Effect of zinc oxide nanoparticles on germination and seedling growth of wheat under salinity stress. *Journal of Plant Physiology*, 233, 80–88.
17. Siddiqui, M. H., Al-Whaibi, M. H., Faisal, M., and Al Sahli, A. A. (2020). Role of nanoparticles in plants: Beneficial and harmful effects. *Saudi Journal of Biological Sciences*, 27(4), 1113–1120.
18. Rouphael, Y., and Colla, G. (2020). Biostimulants in agriculture. *Frontiers in Plant Science*, 11, 40.
19. Zhao, Q., Guo, J., Shu, M., Wang, P., and Hu, S. (2020). Impacts of drought and nitrogen enrichment on leaf nutrient resorption and root nutrient allocation in four Tibetan plant species. *Science of the Total Environment*, 723, 138106.
20. Poorter, H., Niinemets, Ü., Ntagkas, N., Siebenkäs, A., Mäenpää, M., Matsubara, S., and Pons, T. (2019).

A meta-analysis of plant responses to light intensity for 70 traits ranging from molecules to whole plant performance. *New Phytologist*, 223(3), 1073–1105.

21. Singh, A., Sharma, A., Singh, O., Rajput, V. D., Movsesyan, H. S., Minkina, T., and Ghazaryan, K. (2024). In-depth exploration of nanoparticles for enhanced nutrient use efficiency and abiotic stresses management: Present insights and future horizons. *Plant Stress*, 100576.
22. Zhang, H., Sun, X., and Dai, M. (2022). Improving crop drought resistance with plant growth regulators and rhizobacteria: Mechanisms, applications, and perspectives. *Plant Communications*, 3(1).
23. Agrahari, S., and Dubey, A. (2020). Nanoparticles in plant growth and development. In *Biogenic Nanoparticles and Their Use in Agro-Ecosystems* (pp. 9–37).
24. Quiterio-Gutiérrez, T., Ortega-Ortiz, H., Cadenas-Pliego, G., Hernández-Fuentes, A. D., Sandoval-Rangel, A., Benavides-Mendoza, A., and Juárez-Maldonado, A. (2019). The application of selenium and copper nanoparticles modifies the biochemical responses of tomato plants under stress by *Alternaria solani*. *International Journal of Molecular Sciences*, 20(8), 1950.
25. Rai-Kalal, P., and Jajoo, A. (2021). Priming with zinc oxide nanoparticles improves germination and photosynthetic performance in wheat. *Plant Physiology and Biochemistry*, 160, 341–351.
26. Abd El-Wahab, M. M., Gabriel, M. Y., Raslan, M., and Farghali, A. A. (2021). Effect of nanoparticles of feldspar and hematite using different levels of chemical potassium fertilizer on yield and protein production of wheat. *IOP Conference Series: Materials Science and Engineering*, 1046(1), 012029.
27. Yang, W., Cheng, P., Adams, C. A., Zhang, S., Sun, Y., Yu, H., and Wang, F. (2021). Effects of microplastics on plant growth and arbuscular mycorrhizal fungal communities in a soil spiked with ZnO nanoparticles. *Soil Biology and Biochemistry*, 155, 108179.
28. Deshmukh, S. K., Kochar, M., Kaur, P., and Singh, P. P. (Eds.). (2023). *Nanotechnology in agriculture and environmental science*. CRC Press.
29. Bhat, J. A., Shivaraj, S. M., and Bhat, M. A. (2022). Nanoparticles in sustainable agriculture: An emerging technology. *Environmental Research*, 204, 112243.
30. Rhaman, M. S., Tania, S. S., Imran, S., Rauf, F., Kibria, M. G., Ye, W., and Murata, Y. (2022). Seed priming with nanoparticles: An emerging technique for improving plant growth, development, and abiotic stress tolerance. *Journal of Soil Science and Plant Nutrition*, 22(4), 4047–4062.
31. Tripathi, S., Tiwari, K., Mahra, S., Victoria, J., Rana, S., Tripathi, D. K., and Sharma, S. (2024). Nanoparticles and root traits: Mineral nutrition, stress tolerance and interaction with rhizosphere microbiota. *Planta*, 260(2), 34.