Journal of Integral Sciences
[An International Open Access Journal]
Available at www.jisciences.com ISSN: 2581-5679

INTERACTIVE EFFECTS OF SOIL-APPLIED NITROGEN AND FOLIAR NANO-UREA ON GROWTH AND GRAIN YIELD OF MAIZE (*ZEA MAYS* L.)

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Received: 08-06-2026 Revised: 19-07-2026 Accepted: 26-08-2026

ABSTRACT
A field experiment was conducted in the spring season of 2025 in Sumer district, Al-Qadisiyah, Iraq, to study the combined effect of soil applied nitrogen and foliar nano nitrogen spray on the growth and grain yield of maize (Zea mays L.). The factorial experiment was laid out in a randomised complete block design with three replications. Three levels of soil nitrogen were tested, namely: N0 (unfertilised control), N1 (50% of the recommended dose) and N2 (100% of the recommended dose). Four concentrations of foliar nano-nitrogen were applied: F_0 (unsprayed control), F_1 (2 mL L^{-1}), F_2 (4 mL L^{-1}), and F_3 (6 mL L^{-1}). X-ray diffraction, Fourier-transform infrared spectroscopy and field-emission scanning electron microscopy characterised the fertiliser as crystalline urea as the main phase with a mean particle diameter of 38.5 nm. Ten growth and yield traits were measured. Main and interaction effects were significant ($P < 0.05$) for most traits. The N_2F_2 combination produced the highest plant height (226.8 cm), chlorophyll content (49.6 SPAD), kernels per ear (548), 100-kernel weight (34.7 g), and grain yield (8.62 t ha^{-1}), representing an 82.6% yield increase over the N_0F_0 control (4.72 t ha^{-1}). Raising the spray to 6 mL L^{-1} gave no significant further gain. N_1F_2 (half the soil nitrogen dose plus 4 mL L^{-1}) gave a grain yield (6.86 t ha^{-1}) statistically equal to that of N_2F_0 (full soil dose without spray, 6.58 t ha^{-1}). Combining soil nitrogen with foliar nano-nitrogen therefore raises maize yield and may reduce soil fertilizer inputs.
Keywords: Nano-nitrogen fertilizer, foliar application, maize, *Zea mays* L., soil nitrogen, grain yield, nano-urea, growth parameters, XRD, FTIR, FESEM.

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DOI: https://doi.org/10.37022/jis.v9i2.158

Produced and Published by
South Asian Academic Publications

INTRODUCTION
Maize (*Zea mays* L.) ranks among the most important cereal crops globally and serves as a staple for food, feed, and industrial raw material. Its productivity is strongly dependent on a sufficient supply of nutrients, with nitrogen being the single most important element controlling vegetative growth, dry-matter accumulation and final grain formation [1]. Nitrogen is a structural element of amino acids, proteins, nucleic acids and chlorophyll. Availability at successive growth stages directly controls photosynthetic capacity, canopy development and biomass partitioning toward the ear [2]. Soil application of nitrogen fertiliser is still the most common delivery method in most cropping systems. However, a large proportion of the applied nitrogen can be lost through leaching, volatilisation and different soil transformation processes, which reduce the fertiliser use efficiency and increases the input cost required to maintain high yields [3]. Such concerns have led to the investigation of more efficient nutrient delivery methods by researchers such as foliar fertilisation and nanotechnology-based fertilisers [4]. Nano-fertilizers are a new class of nutrient carriers with properties that can improve nutrient delivery and uptake. Because of their small particle size, higher surface-area-to-volume ratio and potential for controlled release, they can reach plant tissues through foliar application more efficiently than conventional formulations [5]. Recent field studies on maize have shown that supplying part of the nitrogen requirement from the soil and the rest as foliar sprays of urea or nano-urea can maintain growth and yield at the level of the full soil dose [6,7]. One study reported that combining 100% of the recommended soil nitrogen with foliar nano-urea at 4 mL L^{-1} produced the highest values for plant height, chlorophyll content, and grain

yield, while a 75% soil nitrogen rate supplemented with nano-urea approached the full-rate treatment in several traits [8]. However, few field studies have tested this approach under the arid, irrigated conditions of central and southern Iraq. The best spray concentration under these conditions, and whether foliar nano-nitrogen can replace part of the soil nitrogen dose, are still unclear. Therefore, this study was designed to assess the effect of three soil nitrogen levels and four foliar nano-nitrogen concentrations, and their interaction, on vegetative growth, yield components, and grain yield of maize under field conditions in Al-Qadisiyah Governorate, Iraq. The nano-nitrogen product was also characterized by XRD, FTIR and FESEM to confirm its identity and particle size before use.

MATERIALS AND METHODS

2.1 Nano-Nitrogen Fertilizer Characterization

The nano-nitrogen fertilizer used in this study was a commercial liquid formulation based on nano-scale urea particles intended for foliar application (IFFCO Nano Urea Liquid; Indian Farmers Fertiliser Cooperative Limited (IFFCO), India; nitrogen content 4% w/w). Before field use, its structural and morphological properties were examined by three complementary analytical techniques to confirm the nano-scale nature of the active ingredient. Ten mL of the liquid product was transferred to a clean glass Petri dish and dried in an oven at 60 °C for 24 h . The solid residue thus obtained was ground to fine powder with the help of agate mortar and pestle and was stored in a desiccator till analysis.

2.1.1 X-ray Diffraction (XRD)

The crystalline structure of nano-nitrogen material was determined by X-ray diffractometer (Shimadzu XRD-6000) with Cu Kα radiation (λ = 1.5406 Å) at 40 kV and 30 mA. The scanning range was 2θ=10–70° with a step size of 0.02° and a scan rate of 2°min−1. Average crystallite size (D) was calculated from the (110) reflection using the Scherrer equation, $D = K\lambda/(\beta \cos \theta)$, where K is a shape factor, λ is the X-ray wavelength, β is the full width at half maximum in radians, and θ is the Bragg angle.

2.1.2 Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR spectrometer (Shimadzu IR Affinity-1S) was used to perform functional group analysis in the wavenumber range of 4000-400 cm -1 using the KBr pellet method at a resolution of 4 cm -1 .

2.1.3 Field-Emission Scanning Electron Microscopy (FESEM)

The morphology and particle size distribution of the nano-nitrogen material were characterised using a field-emission scanning electron microscope (FESEM, TESCAN MIRA3). A drop of the diluted fertiliser suspension was placed onto a silicon wafer and covered with a thin layer of gold before being imaged at an accelerating voltage of 15 kV. The diameters of 187 particles were measured on the micrographs using Image J software (version 1.54f, National Institutes of Health, USA), and the mean and standard deviation were calculated.

2.2 Experimental Site and Conditions

The field experiment was conducted at the agricultural fields of Sumer district, Al-Qadisiyah Governorate, Iraq (31°53′ N, 44°58′ E), during the 2025 spring growing season. A relatively uniform plot was selected based on soil characteristics, and representative soil samples were collected from the 0–30 cm depth before planting to determine basic physical and chemical properties. The soil was silty clay loam, with pH 7.4, EC 3.2 dS m^{-1}, organic matter 12.6 g kg^{-1}, and available N, P and K of 38, 11.4 and 186 mg kg^{-1}, respectively.

2.3 Experimental Design and Treatments

The experiment followed a factorial arrangement in a randomized complete block design (RCBD) with three replications. The first factor comprised three levels of soil-applied nitrogen: N_0 (no nitrogen applied), N_1 (50% of the recommended nitrogen dose), and N_2 (100% of the recommended nitrogen dose). The second factor included four concentrations of foliar nano-nitrogen spray: F_0 (unsprayed control), F_1 (2 mL L^{-1}), F_2 (4 mL L^{-1}), and F_3 (6 mL L^{-1}). This gave 12 treatment combinations and a total of 36 experimental units across three blocks. Each experimental unit measured 3 m × 5 m.

2.4 Land Preparation and Sowing

The experimental area was ploughed twice in perpendicular directions, leveled, and divided into individual experimental plots. Seeds of maize (hybrid 5018) were sown on 15 March 2025 in rows 75 cm apart, with 25 cm between plants. Routine agronomic practices, including irrigation, weeding, and pest management, were applied uniformly across all plots throughout the growing season. A basal dose of phosphorus was applied uniformly to all plots at 100 kg P_2O_5 ha^{-1} as triple superphosphate (46% P_2O_5), incorporated into the soil before sowing. No potassium fertilizer was applied, as soil K was adequate.

2.5 Soil Nitrogen Application

The amount of N was applied to the soil at the designated treatment levels. The recommended dose was 240 kg N ha-1 applied as urea (46% N). To increase the nitrogen recovery and minimise losses, the fertiliser dose was split into two equal applications at sowing and at the six-leaf stage (V6, approximately 30 days after sowing). N_1 was applied at 50% of the recommended rate, with N_2 applied at the full 100% recommendation. The N 0 treatment received no nitrogen in the soil.

2.6 Foliar Nano-Nitrogen Spray

The nano-nitrogen spray solutions were prepared in the distilled water at the specified concentrations. The solutions were sprayed with a calibrated hand sprayer. The spraying was done early in the morning, when the weather was good, and there were no strong winds or high temperatures. Two foliar applications were made at active vegetative growth (six-leaf stage, V6, 30 days after sowing) and pre-flowering stage (pre-tasseling stage, VT, 55 days after sowing). Spray volume was the same for all treatments (500 L ha-1).

2.7 Growth and Yield Measurements

Growth traits were recorded on 10 tagged plants from the central rows of each plot. Plant height was recorded at full vegetative maturity, measured from the soil surface to the tip of the tassel. The number of functional leaves per plant was counted manually. Chlorophyll content was estimated non-destructively using a SPAD-502 chlorophyll meter (Konica Minolta) on the ear leaf at silking (R1). Leaf area was determined by the leaf length × maximum width × 0.75 correction factor method (Montgomery, 1911), and stem diameter was measured with a digital Vernier caliper (accuracy 0.01 mm) at the second internode above the soil surface. At physiological maturity, representative plant samples (5 plants per plot) were harvested from each experimental unit to determine the number of ears per plant, ear length, number of kernels per ear, and 100-kernel weight. Grain yield was determined from a harvested area of 4.5 m^2 in the central rows of each plot and converted to t ha^{-1} after adjusting grain moisture to 14%.

2.8 Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate for a factorial RCBD. The significance of soil nitrogen, foliar nano-nitrogen, and their interaction was tested at $P \leq 0.05$. Treatment means were compared using the least significant difference (LSD) at the 5% probability level. All analyses were performed using GenStat statistical software (23rd edition; VSN International, Hemel Hempstead, UK).

RESULTS AND DISCUSSION

3.1 Characterization of the Nano-Nitrogen Fertilizer

XRD, FTIR and FESEM are standard tools for confirming the structure and size of urea-based nano-fertilizers [9]. Such data are also needed because independent information on the structure, dissolution and nitrogen release of commercial nano-urea products is still limited [10].

3.1.1 XRD Analysis

Figure 1 shows the XRD pattern of the fertiliser. It has ten reflections in the range of 2θ = 10-50°. The strongest reflection is at 22.4°, followed by reflections at 24.5°, 29.4° and 35.6°. These four positions correspond to the (110), (101), (111) and (210) reflections of tetragonal urea, CO(NH2)2, at 22.2°, 24.6°, 29.3° and 35.5° [11]. The smaller reflection at 41.8° is close to the urea (102) line at 41.6° [11]. The relative intensities are different from the reference pattern which could be due to preferred orientation of the dried crystals. The other weak reflections, at 13.5°, 16.7°, 19.1°, 32.8° and 47.3°, are not characteristic for the urea pattern [11]. This is probably due to other parts of the formulation, as commercial nano-urea products may contain polymer carriers or stabilisers [10]. The broad urea reflections indicate the presence of small crystalline domains. The mean crystallite size was found to be 26.4 nm by applying the Scherrer equation to the (110) reflection. This value describes only the crystalline domains and is less reliable when the peaks are very broad or when the crystals are strained [12].

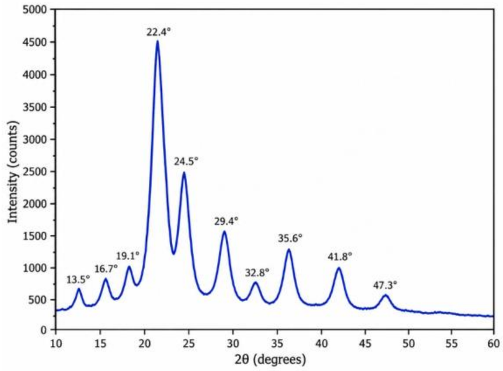

Figure 01: XRD pattern of the nano-nitrogen fertilizer showing the characteristic reflections of crystalline urea

3.1.2 FTIR Analysis

The FTIR spectrum of the fertilizer is shown in Figure 2. Two N–H stretching bands appear at 3440 and 3330 cm^{-1}. They are due to the asymmetric and symmetric stretching of the NH_2 groups [13,14]. The strongest band, at 1680 cm^{-1}, arises from C=O stretching coupled with NH_2 bending (amide I). The band at 1610 cm^{-1} is due to NH_2 bending (amide II), and the band at 1460 cm^{-1} to asymmetric C–N stretching. The weak band at 1160 cm^{-1} is assigned to NH_2 rocking. These positions agree within about 15 cm^{-1} with the bands reported for crystalline urea at 3439, 3345, 1680, 1625, 1468 and 1153 cm^{-1} [15]. The band at 1050 cm^{-1} lies in the region of a second NH_2 rocking mode of urea [16]. C–O stretching of an organic carrier, if present, may also contribute to this band. The band at 760 cm^{-1} is attributed to out-of-plane wagging of the NH_2 and C=O groups [13,14]. Together, these bands confirm that urea is the active ingredient of the fertilizer. No strong bands of other functional groups were detected, so any additives are probably present at low levels, or their bands overlap with those of urea.

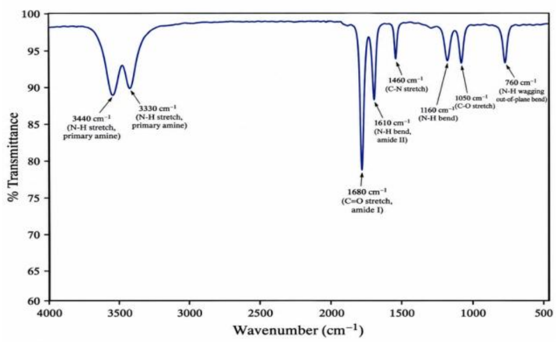

Figure 02: FTIR spectrum of the nano-nitrogen fertilizer confirming urea-based functional groups

3.1.3 FESEM Analysis

FESEM images of the fertilizer are shown in Figure 3. At low magnification (Figure 3a), the particles are roughly spherical and partly agglomerated. At high magnification (Figure 3b), they show a rough, granular surface. The size histogram (Figure 3c) gives a mean diameter of 38.5 ± 9.6 nm (n = 187). The distribution is close to normal, with a slight tail toward larger sizes. Most particles are 20–55 nm in diameter, and the most frequent size class is about 35–39 nm. All measured particles are below 100 nm, so the product falls within the nanoscale range [17]. The mean size is of the same order as the 28.3 nm TEM diameter reported for another commercial nano-nitrogen fertilizer [18]. FESEM measures whole particles, whereas the Scherrer equation gives the size of crystalline domains. A particle may therefore contain more than one crystallite [12]. Two limitations should be noted. First, urea is highly soluble in water, and the particles were imaged after the droplet had dried. Part of the observed morphology may therefore have formed during drying. Second, the particle size in the liquid product was not measured. Dynamic light scattering, as used for other nano-nitrogen products [18], is recommended in future work to confirm the particle size in suspension.

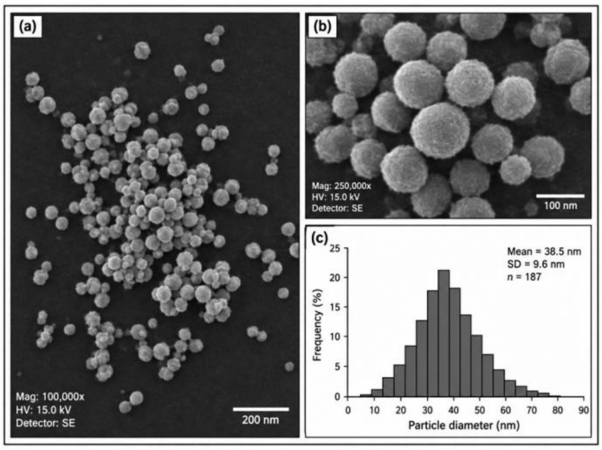

Figure 03: FESEM characterization of the nano-nitrogen fertilizer. (a) Low-magnification FESEM micrograph showing overall particle morphology, (b) high-magnification FESEM image revealing detailed spherical particle structure, (c) particle size distribution histogram of measured particle diameters (n = 187).

3.2 Effect on Vegetative Growth Parameters

The analysis of variance revealed significant effects of soil nitrogen levels, nano-nitrogen spray concentrations, and their interaction on most vegetative growth traits measured. This indicates that the maize response was not governed by a single nitrogen source alone but was influenced by the complementary action of soil-applied and foliar-delivered nitrogen. Plant height and leaf number increased progressively with rising soil nitrogen and nano-nitrogen spray concentration up to 4 mL L^{-1} (Table 1, Figure 4). The values at 6 mL L -1 were slightly lower but the differences were smaller than the LSD and thus not significant. The N_2F_2 treatment had the tallest plants (226.8 cm) and highest number of leaves (15.1 leaves $plant^{-1}$), while the N_0F_0 control had the shortest plants (181.4 cm) and lowest number of leaves (12.1 leaves $plant^{-1}$). The pattern is due to the role of nitrogen in supporting protein synthesis, chlorophyll formation and meristematic activity. Adequate nitrogen supply during the vegetative phase drives stem elongation and leaf initiation, and the foliar nano-nitrogen spray likely provided a supplementary and rapidly available nitrogen source during periods of peak demand [6,19].

Table 01: Effect of soil nitrogen levels and nano-nitrogen spray on plant height (cm) and number of leaves per plant of maize

Treatment	F_0 (0 mL L^{-1})	F_1 (2 mL L^{-1})	F_2 (4 mL L^{-1})	F_3 (6 mL L^{-1})
	Plant Height (cm)			
N_0 (0% N)	181.4	190.6	196.8	193.1
N_1 (50% N)	198.7	207.5	216.9	212.8
N_2 (100% N)	207.6	217.4	226.8	222.1
LSD 0.05 = 7.8				
	Number of Leaves			
N_0 (0% N)	12.1	12.8	13.2	13.0
N_1 (50% N)	13.4	14.0	14.6	14.3
N_2 (100% N)	14.0	14.5	15.1	14.8
LSD 0.05 = 0.6				

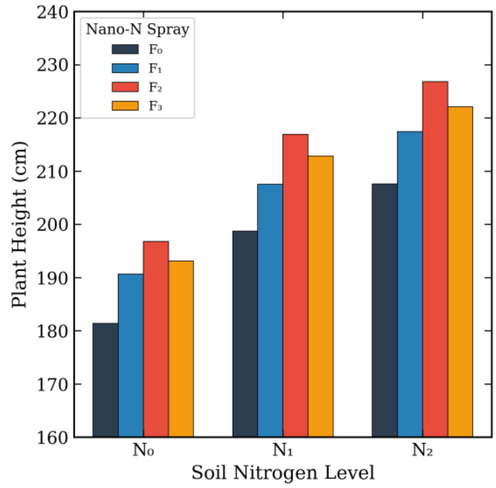

Figure 04: Plant height of maize as affected by soil nitrogen levels and nano-nitrogen spray concentrations

Leaf area, chlorophyll content, and stem diameter followed a similar trend (Table 2, Figure 5). The N_2F_2 combination registered the highest leaf area (576.4 cm^2 $plant^{-1}$), chlorophyll reading (49.6 SPAD), and stem diameter (27.0 mm), whereas N_0F_0 gave the lowest values across all three traits. The increase in chlorophyll content with elevated nitrogen availability is a well-documented physiological response, given that nitrogen is a core constituent of the chlorophyll molecule and the light-harvesting protein complexes of the photosystem [2]. Several recent studies have reported that nano-fertilizer foliar application can improve physiological growth indicators such as chlorophyll concentration and nutrient use efficiency, although the magnitude of response varies with fertilizer type, concentration, and environmental conditions [5,20].

Table 02: Interaction effect of soil nitrogen and nano-nitrogen spray on leaf area, chlorophyll content, and stem diameter of maize

Treatment	Leaf Area (cm^2 $plant^{-1}$)	Chlorophyll (SPAD)	Stem Diameter (mm)
N_0F_0	438.2	37.8	20.6
N_0F_1	462.5	40.2	21.7
N_0F_2	478.6	42.4	22.5
N_0F_3	471.8	41.6	22.1
N_1F_0	491.7	42.8	23.1
N_1F_1	516.3	45.1	24.0
N_1F_2	538.7	47.3	25.1
N_1F_3	529.4	46.5	24.7
N_2F_0	518.6	45.3	24.6
N_2F_1	548.9	47.7	25.8
N_2F_2	576.4	49.6	27.0
N_2F_3	565.2	48.8	26.5
LSD 0.05	18.6	2.1	1.4

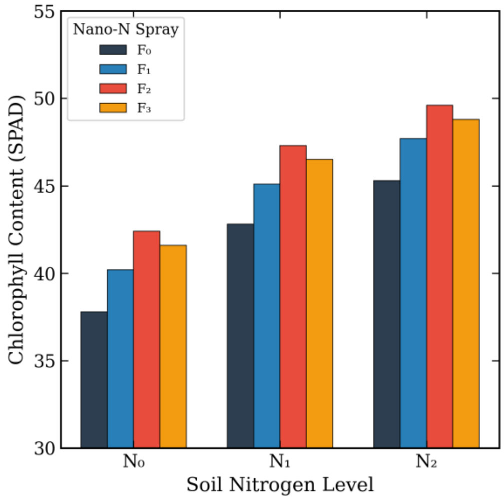

Figure 05: Chlorophyll content (SPAD) of maize leaves under different soil nitrogen levels and nano-nitrogen spray concentrations

3.3 Effect on Yield Components and Grain Yield

Yield components responded significantly to both soil nitrogen levels and nano-nitrogen spray concentrations, and the interaction between the two factors was statistically significant for most traits. The number of ears per plant and ear length increased with rising soil nitrogen and nano-nitrogen spray up to F_2, with the N_2F_2 treatment recording the highest values (1.43 ears $plant^{-1}$ and 23.6 cm, respectively) and N_0F_0 the lowest (1.12 ears $plant^{-1}$ and 17.8 cm) (Table 3). This improvement is attributable to the enhanced vegetative growth and larger leaf canopy produced under higher nitrogen availability, which in turn increased the pool of assimilates directed toward the reproductive organs [21].

Table 03: Interaction effect of soil nitrogen and nano-nitrogen spray on number of ears per plant and ear length of maize

Treatment	Ears $plant^{-1}$	Ear Length (cm)
N_0F_0	1.12	17.8
N_0F_1	1.18	18.6
N_0F_2	1.21	19.3
N_0F_3	1.20	19.0
N_1F_0	1.24	20.1
N_1F_1	1.30	21.0
N_1F_2	1.35	21.8
N_1F_3	1.33	21.5
N_2F_0	1.31	21.4
N_2F_1	1.37	22.3
N_2F_2	1.43	23.6
N_2F_3	1.41	23.1
LSD 0.05	0.08	1.1

Kernels per ear and 100-kernel weight showed a gradual increase with higher soil nitrogen, but the best response was achieved under N_2F_2 (548 kernels ear^{-1} and 34.7 g, respectively), whereas N_0F_0 recorded 382 kernels ear^{-1} and 27.4 g (Table 4; Figures 6 and 7). N_2F_2 did not differ significantly from N_2F_3 in either trait. Sustained nitrogen supply through the grain-filling period likely supported continued photosynthetic activity and assimilate translocation to the developing kernels. The foliar nano-nitrogen spray may have provided a rapid supplemental nitrogen source during stages of high demand, further improving kernel set and filling [7,22]. These results are consistent with a 2025 study that reported the combination of full-rate soil nitrogen with 4 mL L^{-1} nano-urea spray yielded the highest values for plant height, chlorophyll, dry matter, and grain yield in maize, and that a 75% soil nitrogen rate with 4 mL L^{-1} nano-urea produced statistically comparable values for some traits [8].

Table 04: Interaction effect of soil nitrogen and nano-nitrogen spray on number of kernels per ear and 100-kernel weight of maize

Treatment	Kernels ear^{-1}	100-Kernel Weight (g)
N_0F_0	382	27.4
N_0F_1	407	28.5
N_0F_2	426	29.4
N_0F_3	419	29.0
N_1F_0	441	30.2
N_1F_1	467	31.1
N_1F_2	492	32.5
N_1F_3	483	31.8
N_2F_0	481	32.0
N_2F_1	513	33.2
N_2F_2	548	34.7
N_2F_3	537	34.0
LSD 0.05	24.6	1.5

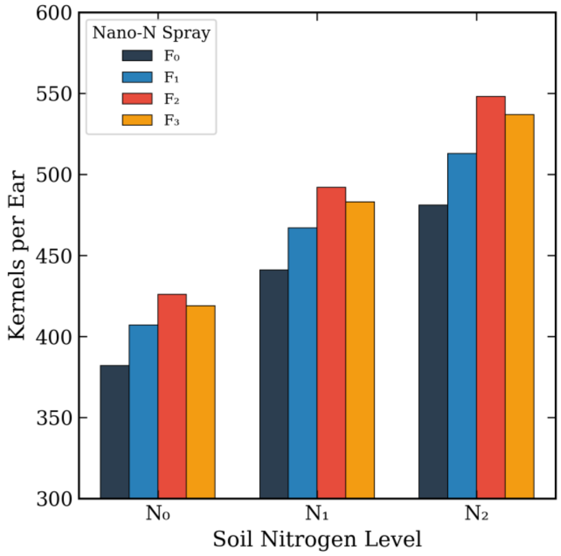

Figure 06: Number of kernels per ear of maize as influenced by soil nitrogen and nano-nitrogen spray treatments

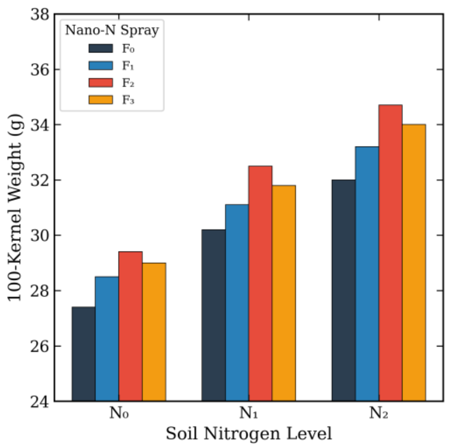

Figure 07: 100-kernel weight (g) of maize as affected by soil nitrogen and nano-nitrogen spray treatments

Grain yield exhibited the most pronounced response to the treatments (Table 5, Figure 8). The N_2F_2 treatment produced the highest grain yield of 8.62 t ha^{-1}, while the control treatment N_0F_0 yielded only 4.72 t ha^{-1}, reflecting an increase of approximately 82.6%. However, N_2F_2 did not differ significantly from N_2F_3 (8.21 t ha^{-1}). The response to spray concentration was therefore not linear. At every soil nitrogen level, 4 mL L^{-1} gave a slightly higher yield than 6 mL L^{-1}, but the differences (0.09–0.41 t ha^{-1}) were smaller than the LSD (0.61 t ha^{-1}). Raising the spray from 4 to 6 mL L^{-1} thus brought no further yield gain, which suggests that the extra nutrient input was not converted into yield [23]. This agrees with the limited and variable uptake of foliar-applied nutrients through the leaf surface [22]. In addition, high foliar urea loads can injure leaf tissue [24].

Table 05: Interaction effect of soil nitrogen and nano-nitrogen spray on grain yield (t ha^{-1}) of maize

Treatment	Grain Yield (t ha^{-1})
N_0F_0	4.72
N_0F_1	5.08
N_0F_2	5.36
N_0F_3	5.27
N_1F_0	5.82
N_1F_1	6.31
N_1F_2	6.86
N_1F_3	6.67
N_2F_0	6.58
N_2F_1	7.35
N_2F_2	8.62
N_2F_3	8.21
LSD 0.05	0.61

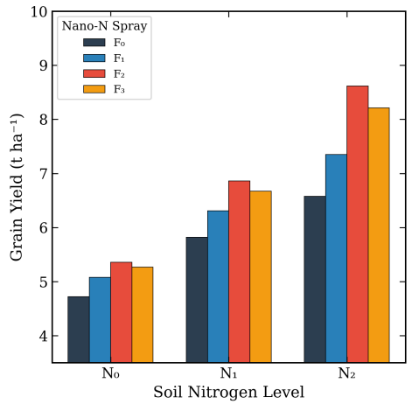

Figure 08: Grain yield (t ha^{-1}) of maize as affected by the interaction between soil nitrogen levels and nano-nitrogen spray concentrations

3.4 Mean Effect of Soil Nitrogen Levels

The overall means for soil nitrogen levels confirmed a clear positive response to increasing nitrogen supply (Table 6, Figure 9). Mean plant height rose from 190.5 cm at N_0 to 218.5 cm at N_2, chlorophyll content from 40.5 to 47.9 SPAD, and grain yield from 5.11 to 7.69 t ha⁻¹. Each step in soil nitrogen raised every trait in Table 06 significantly. Grain yield rose by 1.31 t ha⁻¹ from N_0 to N_1 and by a further 1.27 t ha⁻¹ from N_1 to N_2, so the response to soil nitrogen was nearly linear within the range tested. This pattern reflects the fundamental role of nitrogen in chlorophyll biosynthesis, canopy development, and the partitioning of photosynthetic products into grain [2,25].

Table 06: Mean effect of soil nitrogen levels on selected growth and yield parameters of maize

N Level	Height (cm)	Chl (SPAD)	Ear Length (cm)	Kernels ear⁻¹	100-KW (g)	Yield (t ha⁻¹)
N_0	190.5	40.5	18.7	408	28.6	5.11
N_1	209.0	45.4	21.1	471	31.4	6.42
N_2	218.5	47.9	22.6	520	33.5	7.69
LSD 0.05	4.5	1.2	0.7	15.8	0.9	0.39

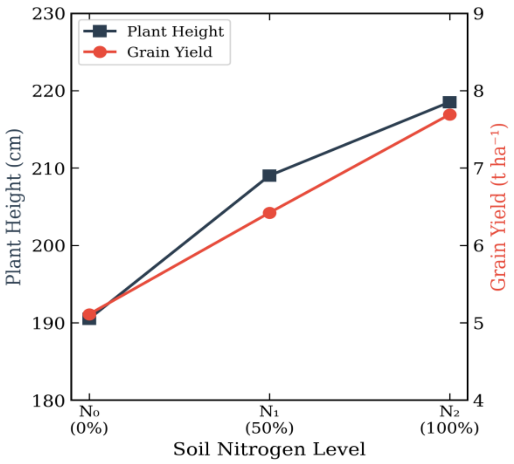

Figure 09: Mean effect of soil nitrogen levels on plant height and grain yield of maize

3.5 Mean Effect of Foliar Nano-Nitrogen Spray

Averaged across all soil nitrogen levels, the nano-nitrogen spray at 4 mL L⁻¹ (F_2) produced the highest mean values for virtually all measured traits (Table 7). Mean grain yield increased from 5.71 t ha⁻¹ at F_0 to 6.95 t ha⁻¹ at F_2, whereas F_3 (6 mL L⁻¹) gave a slightly lower yield of 6.72 t ha⁻¹. Yield rose significantly from F_0 to F_1 and again from F_1 to F_2. In contrast, the difference between F_2 and F_3 (0.23 t ha⁻¹) was smaller than the LSD (0.43 t ha⁻¹), and the same held for every trait in Table 7. Thus, 6 mL L⁻¹ gave no benefit over 4 mL L⁻¹ while using 50% more product. This pattern is practically important because it indicates that increasing the spray concentration does not always lead to a proportional improvement in production. Identifying the optimum foliar concentration is therefore essential for both agronomic efficiency and economic viability [6,26].

Table 07: Mean effect of foliar nano-nitrogen spray on selected growth and yield parameters of maize

Spray Level	Height (cm)	Chl (SPAD)	Ear Length (cm)	Kernels ear⁻¹	100-KW (g)	Yield (t ha⁻¹)
F_0	195.9	42.0	19.8	435	29.9	5.71
F_1	205.2	44.3	20.6	462	30.9	6.25
F_2	213.5	46.4	21.6	489	32.2	6.95
F_3	209.3	45.6	21.2	480	31.6	6.72
LSD 0.05	5.2	1.4	0.8	18.4	1.0	0.43

3.6 Interaction Between Soil Nitrogen and Foliar Nano-Nitrogen

The interaction between the two factors was statistically significant for the majority of measured traits, and the best overall performance was obtained at N_2F_2 (statistically equal to N_2F_3). The benefit of the spray grew with the soil nitrogen level. Compared with F_0, the 4 mL L⁻¹ spray raised grain yield by 0.64 t ha⁻¹ (13.6%) at N_0, by 1.04 t ha⁻¹ (17.9%) at N_1 and by 2.04 t ha⁻¹ (31.0%) at N_2 (Table 5). Foliar nano-nitrogen was thus most effective when the soil nitrogen supply was adequate, which explains the significant interaction. A second practical result concerns N_1F_2 (50% soil nitrogen plus 4 mL L⁻¹). Its grain yield (6.86 t ha⁻¹) did not differ significantly from that of N_2F_0 (100% soil nitrogen without spray, 6.58 t ha⁻¹). The two treatments were also statistically similar in chlorophyll content, stem diameter, ear number and length, kernels per ear and 100-kernel weight (Tables 2–4). In this trial, therefore, two sprays of 4 mL L⁻¹ nano-nitrogen offset the yield loss caused by halving the soil nitrogen dose. These results can be explained by the complementary modes of nitrogen delivery. Soil-applied nitrogen provides a relatively sustained supply to the root zone over the growing season, while foliar nano-nitrogen spray offers a rapid and direct route to the shoot during stages of high nitrogen demand, such as rapid vegetative expansion and early grain filling [7,27]. Field studies in India reached a similar conclusion. Under rainfed semi-arid conditions, full soil nitrogen combined with two nano-urea sprays gave the highest grain yield and nitrogen uptake, and 75% of the recommended nitrogen plus nano-urea gave grain yields statistically similar to the full soil rate [28]. Comparable results were obtained with 75% of the recommended nitrogen plus 4 mL L⁻¹ nano-urea in Karnataka, India [8]. Another 2025 study that combined conventional nitrogen and phosphorus with foliar nano-DAP reported the highest values for several yield components in maize, with some reduced-input treatments performing comparably to the full treatment [29]. The lack of further response at 6 mL L^{-1} may reflect a plateau in foliar nitrogen uptake at about 4 mL L^{-1}, beyond which a higher spray load is not absorbed or assimilated [22]. Alternatively, higher spray concentrations might cause localized osmotic stress or mild injury on the leaf surface [24,30]. Verifying these explanations would require direct measurements of nitrogen uptake and use efficiency, which were beyond the scope of the present study. Nevertheless, the same pattern appeared in almost all measured traits. This supports 4 mL L^{-1} as the most efficient concentration and shows the practical importance of dose optimization in nano-fertilizer programs [31]. The results come from a single season at one site and should be confirmed in multi-season trials.

CONCLUSION

The results of this field study confirmed that the application of nitrogen in soil and foliar spray of nano-nitrogen significantly improved vegetative growth, yield components and grain yield of maize as compared to unfertilised control. The interaction between the two nitrogen sources was significant for most parameters, and the combination of 100% of the recommended soil nitrogen with nano-nitrogen spray at 4 mL L^{-1} (N_2F_2) gave the highest values (statistically equal to N_2F_3), including a grain yield of 8.62 t ha^{-1}, which was 82.6% higher than the control. Increasing the soil nitrogen level from 0% to 50% and then to 100% of the recommendation led to progressive improvements in plant height, chlorophyll content, leaf area, stem diameter, and all yield components. The nano-nitrogen spray showed a positive effect across the measured traits, but the response levelled off at 4 mL L^{-1}, and 6 mL L^{-1} gave no significant further gain. Thus, 4 mL L^{-1} was the most efficient concentration under the conditions of this study. Half the soil nitrogen dose plus 4 mL L^{-1} nano-nitrogen (N_1F_2) gave a grain yield statistically equal to that of the full soil dose without spray (N_2F_0). The nano-nitrogen fertilizer was confirmed as a crystalline urea-based nanomaterial with a mean particle size of 38.5 nm by XRD, FTIR, and FESEM characterization. These findings suggest that integrating soil nitrogen fertilization with foliar nano-nitrogen application can improve maize productivity and may allow partial reduction of soil fertilizer inputs without compromising yield, although confirming this potential requires further multi-season trials with direct nitrogen uptake and use-efficiency measurements and particle-size checks of the liquid product.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

DATA AVAILABILITY

The data supporting the findings of this study are available from the author upon reasonable request.

ACKNOWLEDGEMENTS

The author is grateful to the Central Laboratories at the University of Al-Qadisiyah for performing the XRD, FTIR, and FESEM analyses. The author also thanks the landowners at Sumer district for providing the experimental field site. This study received no external funding.

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