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NANO UREA APPLICATION IMPROVES FRENCH BEAN (*Phaseolus vulgaris* L.) YIELD AND AFFECTS INORGANIC NITROGEN DYNAMICS AND MICROBIAL BIOMASS IN LOWER GANGETIC PLAIN, WEST BENGAL, INDIA

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ABSTRACT

Nitrogen, an essential primary plant nutrient, is often deficient in Indian soils, with only 30–40% of applied urea utilized, while the remainder is lost through leaching, volatilization, denitrification and runoff, reducing efficiency. Nano urea enhances nitrogen dynamics by improving nitrogen use efficiency (NUE), reducing leaching and volatilization losses, and reporting positive effects on nitrogen uptake, microbial activity, and soil health. However, limited field-based evidence is available on the effect of nano-urea on soil nitrogen dynamics and soil physio-chemical, biological properties in French bean under Indian soil conditions. To address this, a study was undertaken during December, 2022-February, 2023 to evaluate the effects of nano urea on yield and NUE, nitrogen dynamics, and a few physio-chemical and biological properties of soil using French bean (*Phaseolus vulgaris* L. cv. Harsha) in a split-plot design. The treatment combinations were as follows: main plots *viz.*; S_1= One stage application {Early vegetative stage (EVS-7 DAS)}, S_2=Two stages application {Early +Late vegetative stage (LVS-28 DAS)}, S_3=Three stages application {Early+ Late+ Flowering Stage (FS-35 DAS)} and sub-plots *viz.*; F_1 to F_6(Basal application of granular and foliar application of nano urea). Results showed short-term positive effects on crop yield, NUE, inorganic N dynamics, microbial biomass, and measured soil properties. Among main treatments, S_3 performed best, while F_6 was superior among sub-treatments. The combined S_3F_6 interaction recorded the highest yield (17.85 t ha^{-1}), NUE (66.62%), organic C (0.71%), microbial biomass C (144.96 mg kg^{-1}) and N (18.12 mg kg^{-1}) and also improved other measured soil properties compared to other treatments and control, indicating their effectiveness in enhancing productivity, while long-term studies are needed to confirm sustained soil-health benefits in the region.

Key words : Alluvial soil, Biomass, Nano-fertilizer, Nitrogen dynamics, Microbial biomass, Nitrogen use efficiency (NUE).

Introduction

The excessive use of fertilizers, insecticides, and herbicides has increased crop yields but caused major environmental and health concerns. Fertilizer consumption rose from 15 to 194 MT (Metric tonnes) between 1950 and 2020 and is expected to reach 263 MT by 2050 (Mittal *et al*., 2020). However, 50–70% of inputs are lost through leaching and other processes, leading to pollution, soil degradation, reduced food quality, and ecosystem disruption (Bollag *et al*., 1992 and Conley *et al*., 2009). Nitrogen deficiency is widespread in Indian soils, especially in light-textured areas, restricting crop growth and productivity. As a key nutrient, nitrogen supports chlorophyll formation, protein synthesis, and enzyme

activity. Despite urea's popularity for its solubility and efficiency, only 30–40% is utilised by plants, with the rest lost through leaching and volatilisation (Bondada *et al.*, 2001). This inefficiency causes environmental pollution.

Nanotechnology, introduced by Norio Taniguchi in 1974, is revolutionizing sustainable agriculture by enhancing productivity and reducing environmental harm. Through nano-formulations, nanoencapsulation, and engineered nanomaterials, it enables precise, controlled delivery of fertilizers and pesticides, minimizing runoff, chemical waste, and ecological disruption while supporting climate resilience (Solanki *et al.*, 2015). Nano-fertilizers are advanced formulations containing particles smaller than 100 nano-meters, derived from conventional fertilizers or plant extracts using chemical, physical, or biological methods (Thakkar *et al.*, 2010). These fertilizers aim to enhance soil fertility, boost crop productivity, and improve the quality of produce (Singh *et al.*, 2017). Liu and Lal (2015) reported that, when engineered at the nanoscale, they provide essential nutrients more effectively to growing plants. Due to their tiny size and high surface-to-volume ratio, nanoparticles offer better nutrient availability and utilization (Lahari *et al.*, 2021 and Khalid *et al.*, 2022). This dramatically improves nutrient use efficiency (NUE)—from around 30% to potentially 80%. Given that fertilizers contribute 35–40% to agricultural production, such improvement is vital, especially in developing countries where agriculture is a key economic driver. The controlled release of nutrients also reduces costs for farmers and lessens soil degradation, preserving the geobiological soil cycle and enhancing food quality and nutrition (Mukhopadhyay *et al.*, 2014; Velmurugan *et al.*, 2021; Patra *et al.*, 2026). With increasing global food demand, nano-based agricultural innovations offer a promising approach to enhance crop productivity and thereby ensure long-term food security.

Nano-urea (IFFCO), produced using spinning cone and nano-channel reactor technologies, has an ideal particle size of 20–50 nm and contains 4–20% nitrogen, supplying 40,000–200,000 mg L^{-1} N. It can reduce conventional urea use by up to 50% and is about 10% more economical (Patidar *et al.*, 2022). Nano urea enhances nitrogen dynamics by improving nitrogen use efficiency, reducing leaching and volatilization losses, and ensuring gradual nutrient release. Its small particle size increases nutrient absorption and translocation within plants (Rani *et al.*, 2024). Nano-fertilizers also stimulate soil microbial biomass carbon and nitrogen by improving nutrient availability and microbial activity, thereby supporting soil fertility and sustainability. Yashaswini *et al.* (2025) reported positive effects of nano urea on nitrogen uptake, microbial activity, and soil health.

However, limited field-based evidence is available on the effect of nano-urea combined with conventional fertilizers on inorganic soil nitrogen dynamics and soil physio-chemical and biological properties through the performance of French bean under Indian soil conditions. French bean (*Phaseolus vulgaris* L.), a protein-rich (23%) short-duration leguminous crop, is considered a poor or inefficient nitrogen fixer because it forms fewer and less effective nodules and is unable to fix atmospheric nitrogen. Therefore, the crop often responds well to external nitrogen fertilization, especially during early growth stages, making it ideal for evaluating nano-fertilizer efficiency. The research specifically aims to understand the fate of nitrogen in the soil and assess how nano-urea enhances nitrogen use efficiency, with the ultimate goal of improving crop productivity and sustainability in nitrogen management. In light of the background information provided, the primary focus of the investigation was to evaluate the effects of granular and nano-urea on yield and NUE of French bean, with particular emphasis on inorganic nitrogen dynamics and certain physicochemical and biological properties of the soil.

Materials and Methods

Experimental location, climate and soil

The research work was conducted during December, 2022–February, 2023 at the AB Block of Bidhan Chandra Krishi Viswavidyalaya, situated in Kalyani, West Bengal (22.97°N, 88.43°E, 9.75 m asl). The site encountered a humid subtropical climate, characterized by hot summers (April–May), monsoonal precipitation (July–September), and relatively short winters (December–January). During the study period, no precipitation was recorded, and the temperature ranged from 10.8°C to 23.8°C. The soil was clay loam in texture with a pH of 7.82, electrical conductivity 0.31 dS m^{-1}, 6.1 g kg^{-1} SOC, 160.0 kg N ha^{-1}, 9.5 kg P ha^{-1}, 180 kg K ha^{-1}, 38.63 kg NH_4^+ ha^{-1} and 17.56 kg NO_3^- ha^{-1}.

Crop Husbandry and treatments

To accomplish the objectives, a field experiment was undertaken in a split-plot design. The treatment combinations (Fig. 1) involved the main plot as crop growth stages application and the subplot as basal application of granular and foliar application of nano urea corresponding to 18 treatments (3-main plot ×6 subplot) replicated thrice (Table 1). Recommended basal dose of

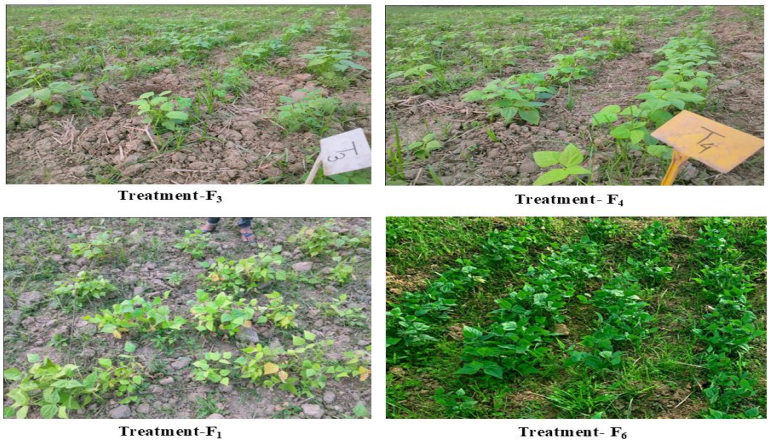


Fig. 1 : A field view of the experiment that received nano urea as treatment, where F_1 (Control) and F_3, F_4, F_6 (Basal application of granular and foliar application of nano urea).

Irrigation management

Supplementary irrigation was provided through the furrow method immediately after sowing for better and rapid germination and during flowering, with additional irrigations applied as required by the crop.

Foliar application of Nano urea

Foliar application of nano urea was carried out as per the treatment doses mentioned in Table 1 at three crop growth stages: (i) early vegetative stage (7 DAS), (ii) late vegetative stage (28 DAS) and (iii) flowering stage (35 DAS). Spraying was done during the early evening hours along the wind direction using a knapsack sprayer.

Table 1 : Treatment combinations of main plot and sub plot under the crop growth stages of French bean.

Main plot	Crop growth stages application[#]		
	S_1	S_2	S_3
	One-stage application	**Two-stage application**	**Three-stage application**
Sub plot	Basal application of granular and foliar application of nano urea		
F_1	Control (eq. to 0 kg N ha^{-1})	Control (eq. to 0 kg N ha^{-1})	Control (eq. to 0 kg N ha^{-1})
F_2	Nano urea[*] @4 ml l^{-1} (500 l ha^{-1} eq. to 0.08 kg N ha^{-1})	Nano urea @2 ml l^{-1} (1000l ha^{-1} eq. to 0.08 kg N ha^{-1})	Nano urea @1.33 ml l^{-1} (1500l ha^{-1} eq. to 0.08 kg N ha^{-1})
F_3	Granular urea @50 kg ha^{-1} (eq. to 23 kg N ha^{-1})	Granular urea @50 kg ha^{-1} (eq. to 23 kg N ha^{-1})	Granular urea @50 kg ha^{-1} (eq. to 23 kg N ha^{-1})
F_4	Granular @37.5 kg ha^{-1}(eq. to 17.25 kg N ha^{-1}) + Nano urea @ 1 ml l^{-1} (500l ha^{-1} eq. to 0.02 kg N ha^{-1})	Granular @37.5 kg ha^{-1} (eq. to 17.25kg N ha^{-1}) + Nano urea @0.5 ml l^{-1} (1000l ha^{-1} eq. to 0.02 kg N ha^{-1})	Granular @37.5 kg ha^{-1}(eq. to 17.25kg N ha^{-1}) + Nano urea @ 0.33 ml l^{-1} (1500l ha^{-1} eq. to 0.02 kg N ha^{-1})
F_5	Granular @25 kg ha^{-1}(eq. to 11.5 kg N ha^{-1}) + Nano urea @ 2 ml l^{-1} (500l ha^{-1} eq. to 0.04 kg N ha^{-1})	Granular @25 kg ha^{-1}(eq. to 11.5 kg N ha^{-1}) + Nano urea @1 ml l^{-1} (1000l ha^{-1} eq. to 0.04 kg N ha^{-1})	Granular @25 kg ha^{-1} (eq. to 11.5 kg N ha^{-1}) + Nano urea @ 0.66 ml l^{-1} (1500l ha^{-1} eq. to 0.04 kg N ha^{-1})
F_6	Granular @12.5 kg ha^{-1}(eq. to 5.75 kg N ha^{-1}) + Nano urea @ 3 ml l^{-1} (500l ha^{-1} eq. to 0.06 kg N ha^{-1})	Granular @12.5 kg ha^{-1} (eq. to 5.75 kg N ha^{-1}) + Nano urea @1.5 ml l^{-1} (1000l ha^{-1} eq. to 0.06 kg N ha^{-1})	Granular @12.5 kg ha^{-1} (eq. to 5.75 kg N ha^{-1}) + Nano urea @1 ml l^{-1} (1500l ha^{-1} eq. to 0.06 kg N ha^{-1})

[#]One-stage application: Early vegetative stage (EVS-7 days after sowing), Two-stage application: {EVS+ Late vegetative stage (LVS-28 days after sowing)}, Three-stage application: {EVS+LVS+ Flowering stage (FS-35 days after sowing)}
[*]Nano urea contains 4% N (w/v) as per the IFFCO product specification.

P and K (40:40 kg ha^{-1}) was applied in all plots. After the basal application of fertilizers, the sowing of French bean (*cv.* Harsha) was done at a seed rate of 2.88 kg ha^{-1} with a spacing of 40.0×10.0 cm^2 with the help of a seed drill. The total number of plots was 18 with a plot size of 4×4 m^2. The duration of the variety was 75–80 days with an average yield of 10–16 t ha^{-1}.

Yield and Yield Attributing traits

At harvest, plant samples were collected using a 1 m^2 quadrant and pods of each plant were counted individually to calculate an average. The pod components were separated and placed in labelled brown paper bags. Afterward, the harvested pods were thoroughly cleaned and dried in a hot air oven to attain the desired moisture

content (10%). The number of seeds per pod, total weight of seeds and seed weight from each plot were recorded and expressed in t ha^{-1} and g, respectively.

Collection of Soil sample and Method used for Soil samples analysis

Soil samples (0–15 cm depth) were collected from each plot two weeks after foliar application of nano urea using a khurpi at three different growth stages of French bean. The samples were placed in plastic bags and kept in a shaded area for five to seven days to dry. Once dried, the soil samples were crushed in a large stone mortar and then sieved through a 2.0 mm mesh sieve. Finally, they were stored in a brown paper inside plastic bags for further analysis. The soils were analysed for pH using a pH meter (Jackson, 1973), electrical conductivity (EC) using a conductivity meter (Jackson, 1973) and soil organic carbon (SOC) by wet digestion method (Walkley and Black, 1934). Soil available nitrogen (N) content was assessed by the alkaline permanganate method (Subbiah and Asija, 1956). Soil samples were extracted with the help of KCl (2 M) and then ammonium (NH_4^+-N) and nitrate (NO_3^--N) N fractions in soil were quantified with the help of the modified Kjeldahl method (Keeney and Nelson, 1982). Total N content in soil was assessed by modified Kjeldahl method (Bremner *et al*., 1982). Microbial biomass carbon (MBC) in soil was assessed with the help of the chloroform fumigation-extraction method (Vance *et al*., 1987), while microbial biomass nitrogen (MBN) was assessed with the help of the method given by Brookes *et al.* (1985).

Nitrogen Use Efficiency

The nitrogen use efficiency (NUE) by French bean was quantified by the following Eq. 1:

$$\text{NUE}(\%) = \frac{\text{N uptake in fertilized plot}\left(\text{kg h}^{-1}\right) - \text{N uptake in control plot}\left(\text{kg h}^{-1}\right)}{\text{N applied}\left(\text{kg h}^{-1}\right)} \times 100 \quad (1)$$

Statistical analysis

For all plant and soil analyses, the means and standard errors of the means were calculated based on three replicates. Statistical analysis was conducted using GRAPES (Gopinath *et al*., 2021) employing analysis of variance (ANOVA) to assess the statistical significance of the treatments. A probability level of p=0.05 was considered the threshold for statistical significance.

Results and Discussion

Yield and Yield attributing traits

Treatments significantly (p<0.05) influenced yield and yield-attributing traits (number of pods $plant^{-1}$, number of seeds pod^{-1}, seed weight) of French bean presented in Table 2. Among the main plot treatments, yield and yield attributing traits of French bean was highest in S_3 (16.69 t ha^{-1}, 19.81, 6.85, 230.88 g), followed by S_2 (16.26 t ha^{-1}, 20.51, 6.19, 230.81 g) and S_1 (15.5 t ha^{-1}, 20.74, 5.38, 228.54 g). Among the sub plots treatments, yield of French bean was highest in F_6 (17.21 t ha^{-1}), followed by different treatment combinations and control F_1 (13.94 t ha^{-1}). Differences between F_5 (16.81 t ha^{-1}) and F_4 (16.60 t ha^{-1}) were minimal, but all treatments exceeded the control by 1.50–3.27 t ha^{-1}. The interaction between growth stages application and form of application rates remarkably affected yield and yield attributing traits of French bean as shown in Table 2. Yield and yield attributing traits of French bean was highest with F_6 recorded 16.55 t ha^{-1}, 21.40, 7.28, 228.69g (one-stage application), 17.11 t ha^{-1}, 22.39, 7.73, 234.80g (two-stages application) and 17.85 t ha^{-1}, 23.07, 8.92, 236.06g (three-stages application), all surpassing their respective control's yields (13.32, 13.78 and 14.74 t ha^{-1}), others yield attributing traits respectively and establishing F_6 as the most effective in improving yield and yield attributing traits of French bean.

Our results showed that the yield range for the control is notably high for zero nitrogen treatment. This could be because of the initial soil available N being 160 kg ha^{-1} this background fertility likely drives the control performance. The combination of granular and nano urea, along with three-stage application, significantly boosted French bean yield compared to only granular, nano urea, and control treatments. Split or stage wise applications positively impacted yield, likely due to improved soil available nitrogen, nitrate nitrogen, organic carbon, and nutrient use efficiency, all contributing to maximum yield levels. Previously, Velmurugan *et al*. (2021) observed that the application of nano urea spray combined with basal application of recommended dose of fertilizer (RDF) led to a 15–21% increase in rice yield. Similarly, Samui *et al*. (2022) reported that the adoption of nano urea through foliar spray at a concentration of 4 ml l^{-1} in combination with 100% of the recommended dose of nitrogen (RDN) applied twice at the knee and tasselling stages of maize crop had a superior impact on morphology, yield attributes, and overall yield of *rabi* maize. Also, Lahari *et al*. (2021) demonstrated that combining 50% of the traditional nitrogen fertilizer application with a foliar spray of nano nitrogen at a concentration of 4 ml l^{-1} during the tillering and before panicle initiation stages significantly increased grain yield (6810 kg ha^{-1}). Furthermore, Patra *et al*. (2026) conducted an experiment and the results showed that the application of different combinations of neem-coated prilled urea (NCPU) and nano urea at

Table 2 : Effect of crop growth stages application and doses of granular and nano-urea on nitrogen use efficiency (NUE) and yield attributing traits of French bean at harvesting stage.

Treatments	NUE (%)	Yield (t ha^{-1})	No. of pods plant^{-1}	No. of seeds pod^{-1}	Seed weights (g)
Main plot-crop growth stages application					
S_1= One-stage application	34.87c	15.5c	20.74a	5.38c	228.54b
S_2=Two-stage application	42.23b	16.26b	20.51b	6.19b	230.81a
S_3= Three-stage application	45.20a	16.69a	19.81c	6.85a	230.88a
LSD (p<0.05)	0.734	0.048	0.1	0.11	1.40
S.Em. ±	3.07	0.35	0.28	0.43	0.77
Subplot-basal application of granular and foliar application of nano urea					
F_1	-	13.94e	18.44e	4.06f	227.28b
F_2	30.43e	15.44d	19.31d	5.27e	228.52ab
F_3	43.32d	16.11c	20.63c	5.49d	228.24ab
F_4	52.24c	16.60b	20.36c	6.70c	231.65ab
F_5	54.17b	16.81b	21.08b	7.58b	232.04a
F_6	64.47a	17.21a	22.29a	7.74a	232.72a
LSD (p<0.05)	1.04	0.39	0.34	0.09	NS
S.Em. ±	9.40	0.49	0.55	0.59	0.95
Interactions					
S_1F_1	-	13.32j	18.12g	3.06h	220.38j
S_1F_2	20.69n	15.04hi	19.24ef	4.43gh	222.44i
S_1F_3	31.89m	15.76fg	19.79e	4.93g	225.43h
S_1F_4	34.39l	15.90efg	19.92de	5.73f	228.50f
S_1F_5	51.70g	16.14efg	20.38d	6.85d	228.33f
S_1F_6	62.19c	16.55cde	21.40c	7.28c	228.69f
S_2F_1	-	13.78j	18.97f	4.39gh	227.48g
S_2F_2	36.22k	15.59gh	19.08ef	4.97g	229.06ef
S_2F_3	43.59j	16.25def	20.64d	5.73f	229.81e
S_2F_4	48.48i	16.66bcd	20.52d	7.02cd	230.32e
S_2F_5	56.39f	16.85bc	20.78cd	7.28c	232.78d
S_2F_6	64.6b	17.11b	22.39b	7.73b	234.80b
S_3F_1	-	14.74i	18.23g	4.73g	231.72de
S_3F_2	48.72hi	15.77fg	19.62e	6.41e	232.78d
S_3F_3	49.34h	16.33def	20.86cd	5.80f	233.68c
S_3F_4	57.62e	16.92bc	21.25c	7.08c	233.43c
S_3F_5	61.42d	17.16b	22.09b	8.17b	235.67ab
S_3F_6	66.62a	17.85a	23.07a	8.92a	236.06a
S.Em. ±	5.27	0.28	0.33	0.36	1.02

One-stage application: Early vegetative stage (EVS-7 days after sowing), Two-stage application: {EVS+ Late vegetative stage (LVS-28 days after sowing)}, Three-stage application: {EVS+LVS+ Flowering stage (FS-35 days after sowing)}. Sub-plot treatment details: F_1 to F_6 are mentioned in Table 1. Duncan's multiple range taste (p<0.05).

various levels increased the growth and yield of sesame.

Nitrogen Use efficiency

Mean values of nitrogen use efficiency of French bean during the research works were presented in Table 2. Treatments significantly (p</ 0.05) influenced on nitrogen use efficiency of French bean. Among the main plot treatments, nitrogen use efficiency was highest under S_3 (45.20%), exceeding S_2 by 2.97% and S_1 by 10.33%. Among the sub plots treatments, nutrient use efficiency was also highest in F_6 (64.47%), followed by F_5 (54.17%), F_4 (52.24%), F_3 (43.32%), F_2 (30.43%), and F_1 (0%). Differences between F_5 and F_4 were minimal, but all treatments exceeded the control by 30.43–64.47%. The interaction between growth stages application and form of application rates markedly significantly affected

nitrogen use efficiency (%) as shown in Table 2. F_6 achieved the maximum values *viz.*; 62.19% (one-stage application), 64.6% (two-stages application) and 66.62% (three-stages application), all exceeding controls (62.19–66.62%).

Our results showed that the combination of granular and nano urea with the three-stage application method enhanced nitrogen use efficiency to the greatest extent as compared to the treatment of only granular and nano urea, as well as the control. Split application directly influenced the nitrogen use efficiency. The reason might be nano urea, with its smaller particle size, increased surface area, release kinetics and interaction with soil colloids could enhance the contact between the fertilizer and plant roots. This improved contact could result in better nutrient uptake and utilization by the plants and the prevention of leaching and also volatilization losses. Similarly, Lahari *et al*. (2021) demonstrated that combining 50% of the traditional nitrogen fertilizer application with a foliar spray of nano nitrogen at a concentration of 4 ml l^{-1} during the tillering and before panicle initiation stages, significantly increased nitrogen use efficiency. Previously, Velmurugan *et al*. (2021) observed that the enhanced efficiency of nano urea resulted in nitrogen fertilizer savings of 25–34 % and directly influenced in nitrogen use efficiency. Also, Rani *et al*. (2024) showed that foliar sprays of nano urea combined with the recommended dose of nitrogen (RDN) improved nitrogen use efficiency (NUE) in wheat. Furthermore, Patidar *et al*. (2022) reported that the highest nitrogen uptake in grain (1.907%) and straw (0.490%) was achieved through the application of nitrogen dosage (RDN) combined with two applications of nano urea during the tillering and jointing phases.

Soil available Nitrogen at three different Growth Stages of French bean

Mean soil available nitrogen at three growth stages of French bean was shown in Table 3, indicating significant (p<0.05) effects of both main and sub-plot treatments throughout the experiment. At the early vegetative stage, among the main plot treatments available N was highest under the three-stage application (S_3), with a value of 71.84 mg kg^{-1}. And the subplot treatments, F_6 recorded the highest available N (74.52 mg kg^{-1}), followed by F_5, F_4, F_3 and F_2. All these treatments recorded significantly higher available N than the control (F_1), that recorded 64.17 mg kg^{-1}. A significant interaction was observed, and under S_1, S_2 and S_3, F_6 recorded highest available N values of 79.01, 79.14 and 82.35 mg kg^{-1}, respectively, as compared to control ranging 63.45–69.76 mg kg^{-1} available N. At the late vegetative stage, the highest available N was recorded under S_3 (73.45 mg kg^{-1}) and F_6 (74.65 mg kg^{-1}) among the main and subplot treatments, respectively. A significant interaction between main and subplots was observed with F_6 and recorded 75.32, 76.83 and 76.84 mg kg^{-1} highest available N under S_1, S_2 and S_3, respectively, as compared to control (64.92–69.74 mg kg^{-1}). At harvest, available N was highest again under S_3 (73.92 mg kg^{-1}) and F_6 (80.07 mg kg^{-1}) among the main and subplot treatments, respectively. Across the crop growth stages, F_6 recorded the highest available N under S_1, S_2 and S_3, with values ranging from 75.58 to 76.41 mg kg^{-1}.

These results highlighted typical trends that the F_6 treatment under the three-stage applications was most effective in enhancing soil available nitrogen along the crop phenology compared to individual treatments and control. Stage-wise application of nano urea in French bean increases available soil nitrogen through controlled nutrient release, reduced nitrogen losses, and improved nitrogen use efficiency. It also enhances microbial activity, nutrient mineralization, and rhizosphere processes, ensuring continuous nitrogen availability throughout crop growth stages and leaving higher residual nitrogen in the soil. Similarly, Lahari *et al*. (2021) reported that combining 50% of the traditional nitrogen fertilizer application with a foliar spray of nano nitrogen at a concentration of 4 ml l^{-1} during the tillering and before panicle initiation stages, significantly increased soil available nitrogen (147.7 kg ha^{-1}). Previously, Kannoj *et al*. (2022) conducted a field experiment and their findings revealed that the treatment combination of 50% conventional urea and 50% nano urea fertilizer, resulted in the highest nitrogen (N) content and uptake in both grain and straw compared to the other treatments.

Ammoniacal Nitrogen Fractions at three different Growth stages of French bean

Mean ammoniacal nitrogen fractions at three growth stages of French bean were presented in Table 3, significantly (p<0.05) influenced by both main and sub-plot treatments. At the early vegetative stage, the one-stages application (S_1) recorded the highest ammoniacal nitrogen (17.48 mg kg^{-1}), followed by S_2 and S_3. Among subplots, F_3 showed the maximum value (18.08 mg kg^{-1}), followed by F_4, F_6, F_5 and F_2, all exceeding the control (F_1, 15.36 mg kg^{-1}). Significant interaction effects were observed, with F_3 recording 19.17, 18.83 and 17.59 mg kg^{-1} under S_1, S_2, and S_3, respectively, outperforming controls (15.98–14.66 mg kg^{-1}). At the late vegetative stage, S_1 again showed the highest ammoniacal nitrogen

Table 3 : Effect of crop growth stages application and doses of granular and nano-urea on inorganic nitrogen fractions (mg kg^{-1}) in soil at three deferent growth stages of French bean.

Treatments	Early vegetative				Late vegetative				Harvesting			
	Available N	NH_4^+	NO_3^-	Total N	Available N	NH_4^+	NO_3^-	Total N	Available N	NH_4^+	NO_3^-	Total N
S_1	70.82b	17.48a	28.87b	2021.55a	72.21c	15.88a	54.26c	1781.13a	73.30ab	17.16a	32.80c	1492.02a
S_2	71.6a	16.90b	29.32a	2001.51b	72.55b	15.46b	54.52b	1768.63b	73.82a	17.11ab	33.31b	1452.94b
S_3	71.84a	16.77b	29.43a	1984.92c	73.45a	15.44b	55.82a	1749.74c	73.92a	16.77b	33.67a	1443.23c
LSD (<0.05)	0.82	0.18	0.17	11.16	0.54	0.04	0.21	13.89	0.72	0.08	0.19	5.90
S.Em. ±	0.31	0.22	0.17	10.59	0.37	0.14	0.48	9.12	0.19	0.12	0.25	14.91
F_1	64.17e	15.36e	26.54d	1825.6f	66.20e	14.75d	51.45e	1633.03f	67.18d	15.35d	31.25d	1320.17e
F_2	70.54d	16.79d	29.05c	1964.12e	71.85d	15.39bcd	53.84d	1743.34e	73.70c	17.02c	32.52c	1462.39d
F_3	72.30c	18.08a	29.19bc	2079.51a	72.42c	16.50a	54.31c	1866.59a	74.57bc	18.00a	33.20bc	1569.63a
F_4	73.19bc	17.55b	30.25ab	2072.62b	74.20b	16.03ab	55.51b	1793.95b	75.62b	17.32b	34.18ab	1494.09b
F_5	73.24b	17.10c	29.87b	2062.87c	73.94bc	15.73b	55.46bc	1786.85c	74.62bc	17.24bc	33.78b	1465.62c
F_6	74.52a	17.43bc	30.31a	2011.26d	74.65a	15.65bc	58.64a	1775.23d	80.07a	17.16bc	34.63a	1464.48cd
LSD (<0.05)	3.33	0.32	0.60	34.54	3.23	0.33	1.06	37.32	3.39	0.31	0.69	31.01
S.Em. ±	1.66	0.38	0.57	39.72	1.28	0.24	0.97	31.42	1.70	0.36	0.50	33.04
Interactions												
S_1F_1	63.45g	15.98h	26.38j	1867.98g	69.74c	14.73ij	51.78ef	1640.86i	62f	16.05f	32.25efg	1351.90f
S_1F_2	70.07f	17.01cdef	27.88hi	1934.03f	71.38c	15.26fghij	53.00def	1715.91fgh	71.17d	16.47f	32.73defg	1389.50ef
S_1F_3	74.04c	19.17a	27.89hi	2170.22a	72.12bc	16.72a	55.43cd	1957.46a	71.97c	19.01a	33.09cde	1649.02a
S_1F_4	74.64c	18.52b	29.29efg	2117.64abc	72.39bc	15.51efg	56.03b	1837.43bcd	73.69abcd	16.66def	34.53abcd	1496.03c
S_1F_5	78.58b	17.50c	29.58def	1984.69ef	72.29bc	15.44efgh	53.93bc	1795.11cde	72.84bcd	16.60ef	33.31cde	1492.44c
S_1F_6	79.01b	17.02cde	30.74bc	1934.51f	75.32a	15.43efgh	56.96b	1765.08efg	75.58a	16.52f	34.98abc	1480.94cd
S_2F_1	65.40g	15.42i	27.12ij	1842.08g	66.89d	14.66j	51.44ef	1570.05j	65.45e	14.98g	30.80fg	1349.83f
S_2F_2	70.16f	16.64efg	28.44gh	1961.08f	72.04bc	14.97ghij	51.97ef	1708.26gh	66.79e	16.19f	33.21defg	1411.65e
S_2F_3	73.68cd	18.83ab	28.73fgh	2121.34abc	74.49ab	16.47ab	52.19def	1877.23b	71.13d	18.34ab	32.54cde	1626.57ab
S_2F_4	73.73cd	17.56c	29.75cdef	2103.16bc	75.45a	15.80cdef	57.01b	1852.18bc	73.77abcd	17.98b	34.16abcde	1578.92b
S_2F_5	77.58b	17.37cd	30.72bc	2069.34cd	74.97a	15.70def	53.33de	1802.79cde	71.38d	17.54bcd	33.56bcde	1507.81c
S_2F_6	79.14b	16.81def	31.14b	2032.33de	76.83a	15.29fghi	59.61a	1796.03cde	76.03a	16.94cdef	35.59ab	1477.36c
S_3F_1	69.76f	14.66j	26.13j	1766.73h	64.92d	14.84hij	51.13f	1688.18hi	65.07e	15.01g	30.72g	1258.78g
S_3F_2	70.99ef	16.22gh	29.15efg	1925.99f	70.45c	14.93ghij	55.43bc	1713.27fgh	71.99cd	16.95cdef	32.29efg	1377.36ef
S_3F_3	71.34def	17.59c	29.91cde	2139.14ab	71.40c	16.37abc	55.52bc	1857.41bc	72.85bcd	18.38ab	32.65defg	1506.80c
S_3F_4	73.44cde	17.45c	30.04cde	2082.59bcd	76.21a	16.31abc	56.34b	1780.00def	74.50ab	17.66bc	33.31cde	1483.09c
S_3F_5	78.85b	16.42fgh	30.60bcd	2029.93de	75.47a	16.27abcd	56.25b	1721.66fgh	72.92bcd	17.51bcde	32.87def	1467.66cd
S_3F_6	82.35a	16.72efg	32.18a	1965.15f	76.84a	15.99bcde	60.27a	1718.09fgh	76.41a	17.47bcde	36.12a	1423.47de
S.Em. ±	1.18	0.27	0.39	26.50	0.79	0.15	0.64	21.86	0.95	0.26	0.34	23.25

Main plot treatments- S_1: One-stage application-early vegetative stage (EVS-7 days after sowing), S_2: Two-stage application- {EVS+ late vegetative stage (LVS-28 days after sowing)}, S_3: Three-stage application- {EVS+LVS+ flowering stage (FS-35 days after sowing)}. Sub-plot treatment details: F_1 to F_6 are mentioned in Table 1. Duncan's multiple range taste ($p<0.05$).

(15.88 mg kg^{-1}) and F_3 maintained superiority (16.50 mg kg^{-1}). The interaction between main and subplot treatments remained significant, as F_3 recorded 16.72, 16.47, and 16.37 mg kg^{-1} under S_1, S_2 and S_3, respectively, surpassing controls (14.73–14.84 mg kg^{-1}). At harvest, ammoniacal nitrogen was again maximum under S_1 (17.16 mg kg^{-1}) and F_3 continued to perform best (18.00 mg kg^{-1}). Interaction data confirmed F_3's consistent efficiency, with values of 19.01, 18.34 and 18.38 mg kg^{-1} under S_1, S_2 and S_3, proving it most effective for enhancing soil ammoniacal nitrogen across all stages.

Our results showed that the one-stage application of only granular urea resulted in the highest ammoniacal nitrogen availability, but does not impart into higher yield or NUE of French bean. Basal application of urea at one time in French bean may initially increase ammoniacal nitrogen in soil due to rapid hydrolysis of urea into ammonium (NH_4^+). However, this does not necessarily improve nitrogen use efficiency (NUE) or yield because a large portion of nitrogen may be lost through volatilization, leaching, nitrification, and denitrification before crop uptake. Moreover, a single basal dose may not synchronize with the crop's nitrogen demand during later growth stages, leading to inefficient utilization of nitrogen and lower yield response despite higher ammoniacal nitrogen availability in soil. Similarly, Zhou *et al*. (2022) reported that deep application significantly increased NH_4^+-N concentration at their fertilization points as compared to the surface application. Furthermore, the NH_3 volatilization from large granular treatment was 7.6–11.0% lower than that in the row application. Similar trends were observed at the late vegetative and harvesting stages, though the values were slightly lower at the late vegetative stage and a little bit higher at the harvesting stage. This might be due to increased nitrification of ammonium to nitrate, to which French bean responds strongly at the late vegetative stage and a lower nitrification rate and nutrient uptake due to less nutritional demand of French bean being already attained, with attributes traits at the harvesting stage. Previously, Guo *et al*. (2002) reported that, French bean with three treatments were compared: sole nitrate (NO_3^-) supply (NN), sole ammonium (NH_4^+) supply (AA) and spatially separated supply of NO_3^- and NH_4^+ (NA). After 9 days of treatment onset, NN plants had higher root (36%) and shoot dry matter (11%) than AA plants. Recently, Kumar *et al*. (2024) reported that nano urea reduced nitrogen losses (including NH_4^+-N leaching/ volatilization) compared to conventional urea, with implications for soil nitrogen retention.

Nitrate Nitrogen Fractions at three different Growth Stages of French bean

Mean nitrate nitrogen fractions across three growth stages of French bean were presented in Table 3, showing significant ($p<0.05$) effects of both main and sub-plot treatments. During the early vegetative stage, the three-stage application (S_3) recorded the highest nitrate nitrogen (29.43 mg kg^{-1}), which was slightly higher than those of S_2 and S_1. Among subplot treatments, F_6 showed the maximum value (30.31 mg kg^{-1}), followed by F_4 and F_5, all significantly above the control. Interaction effects revealed that F_6 under S_1, S_2, and S_3 recorded 30.74, 31.14, and 32.18 mg kg^{-1}, respectively, outperforming controls (26.38–26.13 mg kg^{-1}). At the late vegetative stage, S_3 again showed the highest nitrate nitrogen (55.82 mg kg^{-1}) and among subplots, F_6 maintained superiority (58.64 mg kg^{-1}), all significantly higher than the control (51.44 mg kg^{-1}). The F_6 treatment under S_1, S_2 and S_3 achieved 56.96, 59.61 and 60.27 mg kg^{-1}, respectively, surpassing corresponding controls (51.78–51.13 mg kg^{-1}). At harvest, nitrate nitrogen was again highest under S_3 (33.67 mg kg^{-1}), followed by S_2 and S_1. Among subplots, F_6 remained best (34.63 mg kg^{-1}), followed by F_4, F_5, F_3 and F_2 with all exceeding F_1 (31.25 mg kg^{-1}). Interaction analysis confirmed F_6, achieving 34.98, 35.59, and 36.12 mg kg^{-1} under S_1, S_2, and S_3, respectively, indicating its superior efficiency in enhancing nitrate availability throughout the crop cycle.

Our results demonstrated that, the combination of granular and nano urea with three stage applications enhanced soil nitrate nitrogen to the greatest extent as compared to the treatment only granular and nano urea as well as control at three different growth stages of French bean. Split application directly influenced the soil nitrate nitrogen, enhanced maximum and attained higher values at late vegetative growth stage of French bean. As there was a limited study available yet, reason could be the application of different fertilizer combinations at the early vegetative stage led to a lower nitrification rate, and increased over the time as rising organic carbon boosts microbial activity, ultimately leading to higher nitrate levels in the soil. Similarly, Motasim *et al*. (2021) reported that the mineralization of urea fertilizer mostly regulated the nitrogen dynamics in the soil. At the same application rate, higher NH_4^+-N and NO_3^-N concentrations were recorded in the LU (Liquid Urea) applied soils throughout the incubation period in case of N mineralization. At harvesting stage all the treatments followed previous stage trends like early and late vegetative stages and achieved little lower amount available nitrate nitrogen. The possible reason might be, the nutrient uptake increased from

vegetative growth stage to maturity stage as French bean showed a strong response to nitrate ions during this period for better yield attributes traits. Previously, Chaudhari *et al*. (2025) demonstrated that combination of granular and nano urea significantly enhanced N uptake and available N as well as maintained higher soil ammonium-N and nitrate-N levels compared to conventional fertilization.

Total Nitrogen in Soil at three different Growth Stages of French bean

Mean total nitrogen values across three growth stages of French bean are shown in Table 3, revealing significant (p<0.05) effects of both main and sub-plot treatments. During the early vegetative stage, the one-stage application (S_1) recorded the highest total nitrogen (2021.55 mg kg^{-1}). Among sub-plot treatments, F_3 showed the maximum total nitrogen (2079.51 mg kg^{-1}), slightly higher than F_4 and F_5, and notably above the control by 138–247 mg kg^{-1}. Interaction effects indicated F_3 under S_1, S_2 and S_3 recorded 2170.22, 2121.34 and 2139.14 mg kg^{-1}, respectively, outperforming their controls. At the late vegetative stage, total nitrogen again peaked under S_1 (1781.13 mg kg^{-1}), while F_3 remained highest (1866.59 mg kg^{-1}) among subplots. All treatments exceeded the control by 110–233 mg kg^{-1}. Interaction data showed F_3 recorded 1957.46, 1877.23 and 1857.41 mg kg^{-1} under S_1, S_2, and S_3, surpassing respective controls. At the harvesting stage, S_1 again recorded the highest total nitrogen (1492.02 mg kg^{-1}). F_3 maintained superiority (1569.63 mg kg^{-1}), followed by F_4, F_5, F_6 and F_2, all above the control (1320.17 mg kg^{-1}). The interaction of S_1F_3 (1649.02 mg kg^{-1}) showed the highest improvement, confirming F_3's consistent effectiveness in enhancing total soil nitrogen across all growth stages.

The study revealed that applying only granular urea in one stage resulted in the highest total soil nitrogen (organic and inorganic N) compared to other combinations and the control, because a considerable portion of applied nitrogen remains temporarily stored in soil as ammoniacal, nitrate, or organic nitrogen forms. However, this higher total soil nitrogen does not necessarily improve nitrogen use efficiency (NUE) or yield because nitrogen availability may not synchronize with the crop's nitrogen demand during later growth stages. Recently, Chudasama *et al*. (2024) reported that higher total N with full conventional urea in soil, but nuances when integrated with nano urea, coincided with our findings. At the late vegetative and harvesting stage, all treatment combinations followed similar trends but showed comparatively lower total nitrogen. Limited research exists on this topic; the reason could be the smaller particle size and greater surface area. Nano urea ensured better contact with plant roots, enhancing nutrient uptake and efficiency. As French bean plants absorb more nutrients during stage-application, particularly during active growth phases, the increased uptake in addition to microbial immobilization, mineralization–nitrification processes, substantial nitrogen losses through volatilization, leaching and denitrification could lead to a reduction in total nitrogen content in the soil. Previously, Dhoke *et al*. (2013) reported that reduced particle size results in a higher specific surface area and a number of particles $unit^{-1}$ area of a fertilizer, which provides more ability to interact with nano-fertilizers, resulting in greater nutrient penetration and absorption. These nano-scale properties aid uptake in plants. Similarly, Yashaswini *et al*. (2025) reported that the application of granular and nano urea can maintain or enhance critical soil chemical properties, offering a promising strategy for improving nutrient use efficiency and soil health in sustainable crop production systems.

Organic Carbon in soil at three different Growth Stages of French bean

Mean organic carbon values at three growth stages of French bean were shown in Table 4, indicating that organic carbon content was significantly (p<0.05) influenced by both main and sub-plot treatments. At the early vegetative stage, the three-stage application (S_3) recorded the highest organic carbon (0.60%). Among subplot treatments, F_6 showed the maximum value (0.62%), followed by F_5 and F_4 (0.60%), all exceeding the control by 0.11–0.14%. Interaction effects were significant, with F_6 recording 0.61%, 0.64% and 0.69% under S_1, S_2 and S_3, respectively, compared to controls (0.45–0.56%). At the late vegetative stage, S_3 again showed the highest organic carbon (0.66%). Among subplot treatments, F_6 remained superior (0.69%), while all treatments exceeded the control (0.58%) by 0.06–0.11%. Interaction results confirmed that F_6 achieved 0.68% and 0.70% under S_1 and S_2 (vs 0.56% and 0.63% control) and 0.7% under S_3 (vs 0.63% control). At harvest, organic carbon content remained highest under S_3 (0.67%), and among subplot treatments, F_6 again exhibited the maximum organic carbon (0.70%). Interaction effects showed that F_6 recorded 0.71%, 0.72%, and 0.72% under S_1, S_2 and S_3, respectively, confirming F_6 as the most effective treatment for improving soil organic carbon across all growth stages.

These results confirmed that combined granular and nano urea application, particularly F_6 under the three-stage applications, effectively and significantly increased soil organic carbon as compared to individual treatments and the control. However, this observation is limited by a single-season study. This effect could be attributed to

Table 4 : Effect of crop growth stages application and doses of granular and nano urea on organic carbon, pH and electrical conductivity (EC) in soil at three different growth stages of French bean.

Treatments	Early vegetative			Late vegetative			Harvesting		
	Organic C (%)	pH	EC (dS m^{-1})	Organic C (%)	pH	EC (dS m^{-1})	Organic C (%)	pH	EC (dS m^{-1})
Main plot-crop growth stages application									
S_1= One-stage application	0.56c	7.91a	0.35a	0.65a	7.928a	0.34b	0.64b	7.87a	0.41a
S_2=Two-stage application	0.58b	7.90a	0.35a	0.65a	7.77a	0.35b	0.65ab	7.77a	0.42a
S_3= Three-stage application	0.60a	7.90a	0.35a	0.66a	7.782a	0.36a	0.67a	7.89a	0.41a
LSD (p<0.05)	0.01	NS	NS	NS	NS	0.01	0.01	NS	NS
S.Em. ±	0.01	0.00	0.00	0.00	0.05	0.01	0.01	0.04	0.00
Sub plot-basal application of granular and foliar application of nano urea									
F_1	0.48d	7.94a	0.33a	0.58d	7.90a	0.32c	0.56c	7.90a	0.39a
F_2	0.59c	7.92a	0.36a	0.64c	7.85a	0.35bc	0.62bc	7.84a	0.42a
F_3	0.59bc	7.81a	0.35a	0.65bc	7.77a	0.35ab	0.67abc	7.79a	0.42a
F_4	0.60b	7.9a	0.34a	0.68b	7.78a	0.35ab	0.68ab	7.83a	0.42a
F_5	0.60b	7.91a	0.36a	0.68b	7.82a	0.38a	0.69abc	7.80a	0.42a
F_6	0.62a	7.93a	0.36a	0.69a	7.84a	0.35ab	0.70a	7.89a	0.41a
LSD (p<0.05)	0.02	NS	NS	0.02	NS	0.02	0.02	NS	NS
S.Em. ±	0.02	0.02	0.00	0.02	0.02	0.01	0.02	0.02	0.01
Interactions									
S_1F_1	0.45r	7.93a	0.33a	0.56h	7.99a	0.33a	0.55f	7.98a	0.38a
S_1F_2	0.47 hi	7.94a	0.37a	0.59fg	7.97a	0.32a	0.60e	7.84a	0.43a
S_1F_3	0.52g	7.71a	0.35a	0.60f	7.85a	0.35a	0.64d	7.76a	0.40a
S_1F_4	0.56ef	7.98a	0.35a	0.62de	7.95a	0.35a	0.66cd	7.91a	0.42a
S_1F_5	0.59de	7.96a	0.34a	0.64cd	7.88a	0.35a	0.67bc	7.8a	0.42a
S_1F_6	0.61cd	7.92a	0.36a	0.68ab	7.93a	0.34a	0.71a	7.95a	0.42a
S_2F_1	0.54f	7.94a	0.33a	0.63d	7.71a	0.31a	0.57f	7.81a	0.40a
S_2F_2	0.54f	7.91a	0.35a	0.64cd	7.9a	0.35a	0.63d	7.82a	0.42a
S_2F_3	0.55ef	7.84a	0.35a	0.65bcd	7.79a	0.34a	0.65cd	7.74a	0.45a
S_2F_4	0.58de	7.8a	0.34a	0.68ab	7.68a	0.36a	0.66cd	7.79a	0.42a
S_2F_5	0.62c	7.9a	0.36a	0.68ab	7.65a	0.39a	0.68b	7.62a	0.43a
S_2F_6	0.64b	8a	0.35a	0.70a	7.89a	0.35a	0.72a	7.83a	0.41a
S_3F_1	0.56ef	7.96a	0.33a	0.63d	7.99a	0.32a	0.57f	7.9a	0.40a
S_3F_2	0.61cd	7.9a	0.35a	0.66bc	7.69a	0.37a	0.64d	7.87a	0.41a
S_3F_3	0.61cd	7.88a	0.35a	0.68ab	7.68a	0.37a	0.68b	7.87a	0.41a
S_3F_4	0.63bc	7.92a	0.34a	0.69ab	7.72a	0.36a	0.68b	7.8a	0.42a
S_3F_5	0.66ab	7.87a	0.37a	0.70a	7.92a	0.40a	0.71a	7.99a	0.41a
S_3F_6	0.69a	7.88a	0.36a	0.71a	7.69a	0.37a	0.72a	7.88a	0.41a
S.Em. ±	0.01	0.02	0.00	0.01	0.03	0.01	0.01	0.02	0.00

One-stage application: Early vegetative stage (EVS-7 days after sowing), Two-stage application: {EVS+ Late vegetative stage (LVS-28 days after sowing)}, Three-stage application: {EVS+LVS+ Flowering stage (FS-35 days after sowing)}. Sub-plot treatment details: F_1 to F_6 are mentioned in Table 1. Duncan's multiple range taste (p<0.05).

frequent split applications and the efficient nutrient delivery of nano urea, driven by its small particle size, release kinetics, interactions with soil colloids, and microbial mediation. Enhanced nitrogen availability improved plant growth and microbial activity, leading to greater root biomass and organic matter input into the soil. These enhanced plant biomass production and residues, increased microbial activity, and biologically rapid root exudates contributed to increased soil organic carbon. As limited research exists on nano urea's effect on organic carbon, this finding highlighted its potential role in improving soil carbon. Similarly, Verma *et al*. (2024)

conducted an experiment and the results showed that the application of different combinations of conventional fertilizer and nano urea at various levels increased the soil's chemical properties. Previously, Kumar *et al*. (2021) observed that the integrated application of nano and granular urea promoted beneficial soil microbial communities that helped stabilize soil organic matter and contributed to a rise in SOC content. Also, Yadav *et al*. (2023) found that combined application of 50% recommended dose of granular urea with nano urea (1.5 l ha^{-1}) significantly increased soil organic carbon in legumes due to enhanced biomass production and root exudates.

Soil pH and Electrical Conductivity at three different Growth Stages of French bean

Soil pH and electrical conductivity were not significantly affected (p<0.05) by main or subplot treatments, nor by the interaction of stage applications and combinations of form of application rates of urea during the different growth stages of French bean in the experimental study (Table 4).

Soil Microbial Biomass Carbon (SMBC)

Mean values of microbial biomass carbon during the experimental study were presented in Table 5. Treatments significantly (p<0.05) influenced microbial biomass carbon at the harvesting stage. Among the main plot treatments, the three-stage application (S_3) recorded the highest microbial biomass carbon (134.55 mg kg^{-1}), exceeding the one-stage (S_1) and two-stage (S_2) applications methods. Among the sub-plot treatments, F_6 recorded the highest microbial biomass carbon (140.01 mg kg^{-1}) and was significantly higher than the control F_1 (124.36 mg kg^{-1}). The interaction between stages of application and combinations of application rates markedly affected microbial biomass carbon (mg kg^{-1}) as shown in Table 5. Among the growth stages applications, the highest values were obtained with F_6 *viz*.; 139.65 mg kg^{-1} in the one-stage application method (control: 120.90 mg kg^{-1}), 144.18 mg kg^{-1} in the two-stages application (control: 126.38 mg kg^{-1}) and 144.96 mg kg^{-1} in the three-stages application (control: 125.79 mg kg^{-1}), confirming its superiority in enhancing microbial biomass carbon.

Our results demonstrated that the combination of granular and nano urea along with the three-stage application method enhanced soil microbial biomass carbon to the greatest extent as compared to the treatment of only granular and nano urea, as well as the control. The reason might be that nano-urea application supports soil microbial biomass carbon by minimizing nitrogen shock and fostering microbial activity. When used in combination with granular urea, it improved microbial carbon by sustaining soil organic carbon and microbial biomass. Similarly, Upadhyay *et al*. (2024) reported that nano-urea with conventional fertilizers in wheat–maize systems increased SMBC under nano-urea treatments and was statistically comparable to full recommended N levels, with some nano treatments maintaining higher SMBC than unfertilized controls. Previously, Upadhyay *et al*. (2023) reported that nano-fertilizers combined with conventional sources significantly influenced soil biological indicators including microbial biomass carbon, showing enhanced SMBC under nano-fertilizer-inclusive treatments that supported our findings.

Soil Microbial Biomass Nitrogen (SMBN)

Mean values of microbial biomass nitrogen during the experimental study were presented in Table 5. Treatments significantly (p<0.05) influenced microbial biomass nitrogen at the harvesting stage. Among the main plot treatments, the three-stages application (S_3) showed the highest microbial biomass nitrogen (16.74 mg kg^{-1}), followed by S_2 (16.71 mg kg^{-1}) and S_1 (16.52 mg kg^{-1}). Among the sub plots treatments, microbial biomass nitrogen content was maximized under F_6 (17.83 mg kg^{-1}). All the treatments surpassed the control by 0.75–2.17 mg kg^{-1}, confirming F_6 as most effective for enhancing microbial biomass nitrogen in soil. The interaction between growth stage applications and combinations of form of application rates markedly affected microbial biomass nitrogen (mg kg^{-1}) as shown in Table 5. Microbial biomass nitrogen was likewise highest with F_6, recording 17.44 mg kg^{-1} (one-stage application), 18.02 mg kg^{-1} (two-stage application) and 18.12 mg kg^{-1} (three-stage application), all surpassing their respective controls (15.53, 15.6 and 16.68 mg kg^{-1}), respectively.

Our results showed that the combination of granular and nano urea with three-stage applications enhanced soil microbial biomass nitrogen to the greatest extent as compared to the treatment of only granular and nano urea, as well as the control. The reason could be increased soil organic carbon that directly influenced the mineralization process, as well as soil microbial biomass and microbial nitrogen and nano urea could influence soil microbial nitrogen by affecting microbial biomass and nitrogen cycling processes. Its controlled nitrogen release reduces ammonium toxicity and promotes a stable microbial environment, indirectly enhancing microbial nitrogen assimilation. Previously, Dhayalan *et al*. (2023) reported that nano-urea increased soil microbial populations (bacteria, fungi, actinomycetes), suggesting positive effects on microbial biomass that is upstream to soil N

Table 5 : Effect of crop growth stages application and doses of granular and nano-urea on soil microbial biomass carbon (SMBC), soil microbial biomass nitrogen (SMBN) and the ratio of SMBC:SMBN at harvesting stage of French bean.

Treatments	SMBC (mg kg^{-1})	SMBN (mg kg^{-1})	SMBC: SMBN
Main plot-crop growth stages application			
S_1= One-stage application	133.61ab	16.52b	7.99a
S_2=Two-stage application	132.67b	16.71a	8.03a
S_3= Three-stage application	134.55a	16.74a	8.05a
LSD (p<0.05)	1.29	0.08	NS
S.Em. ±	0.54	0.07	0.02
Sub plot-basal application of granular and foliar application of nano urea			
F_1	124.36d	15.66d	7.85cd
F_2	131.17c	16.61bc	7.94c
F_3	131.95c	16.41c	7.99c
F_4	135.98b	16.65bc	7.87c
F_5	138.20ab	16.78b	8.17b
F_6	140.01a	17.83a	8.32a
LSD (p<0.05)	2.76	0.34	0.14
S.Em. ±	2.32	0.29	0.08
Interactions			
S_1F_1	120.90g	15.53e	7.79bc
S_1F_2	129.70e	15.86de	7.67c
S_1F_3	132.88d	16.09d	7.79bc
S_1F_4	133.62cd	16.58cd	7.97bc
S_1F_5	138.81bc	16.79c	8.016b
S_1F_6	139.65b	17.44b	8.06b
S_2F_1	126.38f	15.6e	7.71c
S_2F_2	126.68f	15.86de	7.92bc
S_2F_3	126.72f	16.01d	7.97bc
S_2F_4	131.62de	16.11d	7.99b
S_2F_5	140.38b	17.16bc	8.17b
S_2F_6	144.18a	18.02a	8.45a
S_3F_1	125.79fg	16.68c	7.99b
S_3F_2	133.28cd	16.80c	8.02b
S_3F_3	133.94cd	16.89c	8.06b
S_3F_4	135.50c	16.91c	8.06b
S_3F_5	140.00b	17.37b	8.21b
S_3F_6	144.96a	18.12a	8.59a
S.Em. ±	1.60	0.18	0.06

One-stage application: Early vegetative stage (EVS-7 days after sowing), Two-stage application: {EVS+ Late vegetative stage (LVS-28 days after sowing)}, Three-stage application: {EVS+LVS+ Flowering stage (FS-35 days after sowing)}. Sub-plot treatment details: F_1 to F_6 are mentioned in Table 1. Duncan's multiple range taste (p<0.05).

transformations. Recently, He *et al.* (2024) reported that addition of nitrogenous fertilizers significantly increased soil microbial biomass N (MBN) in farmland soils, although effects vary with different rates of nitrogenous fertilizers application, which coincided with our findings.

SMBC: SMBN

Ratio between SMBC and SMBN was not significantly affected (p<0.05) by main plot treatments, but significantly affected by sub-plot treatments as well as the interaction at the harvesting stage of French bean during the experimental study (Table 5). Among the sub-plot treatments, the SMBC: SMBN ratio was maximized under F_6 (8.32), followed closely by F_5 (8.17) and all treatments surpassed the control, ranging from 0.01 to 0.47, confirming F_6 as most effective for enhancing SMBC: SMBN in soil. The interaction between growth stage application and combinations of form and rates of urea application markedly affected SMBC: SMBN as shown in Table 5. SMBC: SMBN was likewise highest with F_6, recording 8.06 (one-stage application), 8.45 (two-stage application) and 8.59 (three-stage application), all surpassing their respective controls (7.79, 7.71 and 7.99).

Our results recorded that the combination of granular and nano urea with three stage applications enhanced SMBC: SMBN to the greatest extent as compared to the treatment of only granular and nano urea as well as control. The reason could be increased soil organic carbon that directly influenced the mineralization process as well as soil microbial biomass and nitrogen. Similarly, Upadhyay *et al.* (2024) reported that nano-urea with conventional fertilizers in wheat–maize systems, SMBC under nano-urea treatments was statistically comparable to full recommended N levels, with some nano treatments maintaining higher SMBC than unfertilized controls. Previously, Dhayalan *et al.* (2023) reported that nano-urea increased soil microbial populations (bacteria, fungi, actinomycetes), suggesting positive effects on microbial biomass upstream of soil N transformations. Recently, He *et al.* (2024) reported that addition of nitrogenous fertilizers significantly alters microbial C: N stoichiometry and community structure in farmland soils, although effects vary with different rates of nitrogenous fertilizers application, which coincides with our findings. Furthermore, Upadhyay *et al.* (2023) reported that nano-fertilizers combined with conventional sources significantly influenced soil biological indicators including SMBC: SMBN, showing enhanced SMBC: SMBN under nano-fertilizer-inclusive treatments that supported our findings.

Conclusion

The combined application of granular urea and

growth stage–based nano urea significantly showed short-term positive effects on crop yield, NUE, inorganic N dynamics, microbial biomass and measured soil properties. This integrated approach enhanced reproductive growth and increased French bean yield in the lower Gangetic plains of West Bengal. Therefore, the combined use of granular and nano urea appears promising for improving French bean productivity in the region. However, the study was limited to a single season and location. Therefore, long-term studies are needed to confirm sustained soil health benefits, economic feasibility, and environmental implications across diverse agroecological conditions.

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CRediT authorship contribution statement

Sidhu Murmu: Conceptualization, Methodology, Supervision.

Biplab: Data collection, Software, Writing –original draft, Formal analysis, Data curation, Visualization.

Abir Choudhury: Conceptualization, Methodology, Formal analysis, Tabulation.

Sovan Debnath: Reviewing and editing.

Samayita Basu: Reviewing and editing.

Susmit Saha: Reviewing and editing.

Soumyajit Mallick: Reviewing and editing

Declaration about use of AI tools

Declared that no generative AI tool was used to prepare the manuscript; however, an AI tool was used to edit and polish the English language.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflict of interest

The authors declare no known conflicts of interest.

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