Effect of Nanofertilizers on Growth Parameters, Yield and Chemical Constituents of Forage Pearl Millet in Calcareous Soil

Ashraf A. M. Habib[1]

ABSTRACT

Fertilizers play a crucial role in enhancing food production, despite their high costs. To optimize their benefits and reduce nutrient loss, it is essential to apply the correct amounts, sources, and combinations at the appropriate times and using suitable methods. In a study focusing on calcareous soils, two types of Nano-fertilizers artificial and commercial were applied as foliar sprays at varying rates alongside different percentages of NPK fertilizers. The findings revealed that applying 75% of the recommended fertilizer doses, combined with artificial Nano-fertilizers, significantly improved foliage fresh yield, achieving a maximum of 115.5 Mg ha^{-1}. This treatment also resulted in higher concentrations of nitrogen, phosphorus, and potassium, as well as a crude protein content of 16.1%. Additionally, the use of commercial Nano-fertilizers at a rate of 2.5 ml L^{-1} without mineral fertilizers yielded the highest dry matter (22.8%) and starch content (16.3%). Overall, the study suggests that utilizing 75% of the recommended fertilizer doses along with artificial Nano-fertilizers are an effective strategy for enhancing nutrient efficiency and soil productivity in arid regions.

Keywords: Integration nutrient sources, accumulation nutrients, quality of yield, internal nutrient efficiency.

INTRODUCTION

A common summer-annual feed crop with excellent nutritional content, pearl millet (*Pennisetum glaucum* L.) is used by livestock farmers for grazing, silage, hay, and green chop. Pearl millet is grown as fodder and as a grain. Compared to maize and sorghum, it may be able to grow in low-fertility soil with an annual mean rainfall of 200 mm. Pearl millet is also a cost-effective one-year forage crop that may be used as emergency feed and consistently yields good results. A significant and extensively grown staple crop in many African nations is pearl millet. It offers an annual summer crop with two uses that is used for human Increasing the yield of several prospective annual forage varieties is gaining attention in Egypt these days due to the ongoing summertime lack of green fodder. A significant and extensively grown staple crop in many African nations is pearl millet. It offers a summer harvest that can be used for both human consumption and animal feed. Because of the crop's resistance to heat and drought, vigorous growth, rapid regrowth following grazing or cutting, high biomass production capacity, and lack of hydrocynide acid, forage farmers are particularly familiar with it in arid and semi-arid regions (Khairwal *et al.*, 2007 and Bramhaiah *et al.*, 2018). Dairy calves can eat the lush, tasty, and nutritious green leaves of pearl millet. It was discovered that the date of forage cutting had a significant impact on both the productivity and regrowth pattern of forage crops. According to Bukhari *et al.* (2011), cutting pearl millet at 75 DAS produced the largest leaf area when compared to cutting at 45 and 60 DAS. According to Habiba *et al.* (2018), the plant's height and leaf area produced the most significant values in the first cut, after which they progressively declined until they reached their lowest values in the third cut. On highly limited or calcareous soils, substantial losses of ammonia NH_3-N gas from applied N fertilizers occurred, reducing N fertilizer use efficiency (Larsen & Gunary, 1962 and Terman & Hunt, 1964). The impact of $CaCO_3$ is mostly due to the generation of ammonium carbonate $(NH_4)_2CO_3$, which decomposes readily and releases NH_3- N (Ali and Habib, 2022).

Chemical fertilizer use has surged in an effort to increase crop yields. The growth characteristics and forage output of forage millet were significantly impacted by an increase in the rate of nitrogen fertilization (Bhilare *et al.*, 2010; Pathan *et al.*, 2010 and Shahin *et al.*, 2013). The expense of chemical fertilizer is understood to be steadily rising. Furthermore, using only inorganic fertilizer harms the production and health of the soil. Due to a variety of losses that raise cultivation costs, contribute to greenhouse gas emissions, and result in suboptimal productivity levels and low-quality produce, the nutrient use efficiencies range from 20–50% for N, 10-25% for P, 70–80% for K, and 2% for micronutrients (Singh *et al.*, 2017). Nonetheless, there are certain health hazards, like the blue infant syndrome and rising cultivation expenses (Naderi and Danesh-Shahraki, 2013). In this regard, nanotechnology (El-Azizy *et al.*, 2021) shows promise, as they can maintain agricultural yield and soil health.

Nanotechnology has the potential to increase agricultural output while lowering environmental

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[1]Soil fertility and Microbiology Dep., Desert Research Center, Cairo, Egypt.
Corresponding author: Aea_2013sc@yahoo.com
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hazards. Fertilizer release can be controlled and/or postponed by employing nanoparticles and nanopowders. Because of their larger specific surface area, higher density of reactive regions, or enhanced reactivity of these regions on the particle surfaces, nanoparticles exhibit high reactivity. These characteristics make it easier for fertilizers and insecticides made in Nano standard to be absorbed (Anonymouse, 2009). Utilizing Nano-fertilizers increases their effectiveness, lowers soil toxicity, lessens the possibility of adverse effects from excessive dosage, and reduces the frequency of additions. The primary functions of Nano-fertilizers are to prolong the fertilizer effect interval and postpone the release of nutrients. Naturally, by making fertilizers better, nanotechnology has the potential to significantly impact energy, the economy, and the environment. As a result, nanotechnology has a great potential to achieve sustainable agriculture, particularly in underdeveloped nations. According to Naderi and Danesh-Shahraki (2013) and Gomaa *et al.* (2016), fertilizing the "Nubaria two" cultivar with foliar Nano-fertilizer (NPK+ micro nutrients) at two or three stages (vegetative, flowering, or filling) in both growing seasons resulted in a significant increase in plant height, pod length, number of pods per plant, number of seeds per pod, 100-seed weight, grain, straw, and biological yield as well as harvest index percent.

By improving plant nutrient uptake, disease molecular treatment, disease detection, preserving soil fertility, and guaranteeing high yields without harming the environment, nanoparticles eco-friendly fertilizers like Nano-NPK liquid have the potential to revolutionize the food and agriculture sectors. A system and technology are used to reduce micron-sized minerals to a scale of 10–100 nm, which are known as nanomaterials (NM). According to Pramanik *et al.* (2020), they are naturally occurring inorganic solids having a well-defined chemical composition and an ordered internal structure. According to Singh *et al.* (2023), wheat growth and absorption may be aided by Nano sources of N, P, and K. The amount of N, P, and K in the soil after harvesting increased somewhat with increasing foliar application of P and K Nano-fertilizers, either alone or in combination The data obtained indicated that the most successful treatment for boosting all growth metrics and improving the chemical properties of berries and leaves was foliar spraying NPK-Nano at higher concentrations (800, 120, and 800 ppm) with 50% of traditional NPK. Therefore, using NPK in Nano form helps to lower the quantity utilized and, in turn, the fertilizer costs (Mohamed *et al.,* 2022 and Mahmoud *et al.*, 2025).

The purpose of this experiment is to assess the beneficial effects of foliar Nano-NPK fertilizer applied at various rates as a potential alternative to decreasing the application rates of conventional NPK fertilizer. Additionally, the study aims to evaluate its influence on vegetative growth and productivity in pearl millet.

MATERIAL AND METHODS

Study Location

Two field studies were carried out in the summer of 2022 and 2023 at the Desert Research Centre's experimental farm, Maryout (latitude 31° 00′ 21″ N, longitude 29° 47' 26″ E), which is close to the Mediterranean coast near Alexandria (Figure 1). The study aimed to evaluate how the combined effects of mineral and Nano-fertilizers affected the forage pearl millet (*Pennisetum glaucuml* L) by means of growth parameters, yield, and chemical contents. The characteristics and water condition of the calcareous sandy loam soil under investigation are shown in Tables (1 and 2). The research area is characterized by dry, scorching summers and semiarid climates devoid of rainfall. According to the USDA soil taxonomy (Nachtergaele, 2001), the soil is categorized as an aridisol. Table (3) displays the average values of the weather data that prevailed during the pearl millet life cycle.

The split-plot design field experiment present three replications and the following 16 treatments: The fertilizer was applied to the respective plots after planting. Nano-fertilizers come from two sources: artificial (A) and commercial (C). 400 litters were fed one foliar spray, and each was applied foliarly three times at a rate of 2.5 ml L^{-1} after 20, 40, and 80 DAS. Mineral fertilizer is applied at 0, 25, 50, 75, and 100% RDF. The plot measured 3.5 x 3 m in length and width (1/400 fed), with an area of 10.5 m². Application of fertilizer plots were uniformly drilled with the recommended doses of fertilizer (Figure 2).

Agricultural Practices

Disk plough tillage was used to prepare the ground. Leveling and ridging came after the plugging depth of 0–20 cm. The soil management strategies included applying 20 t ha^{-1} of compost and adding 2.4 t ha^{-1} of gypsum as a soil conditioner. Fifteen days prior to cultivation, the soil was fertilized with the recommended amounts of phosphorus 140 kg P_2O_5 ha^{-1}, as single super phosphate (SSP). Additionally, three equal amount of urea fertilizer (46% N) were applied at 20, 40, and 80 DAS at a rate of 190 kg N ha^{-1}. Following each cutting, 115 kg K_2O ha^{-1} of potassium sulphate was supplied to the soil. One month following seeding, the plants received foliar applications of Nano-fertilizers.

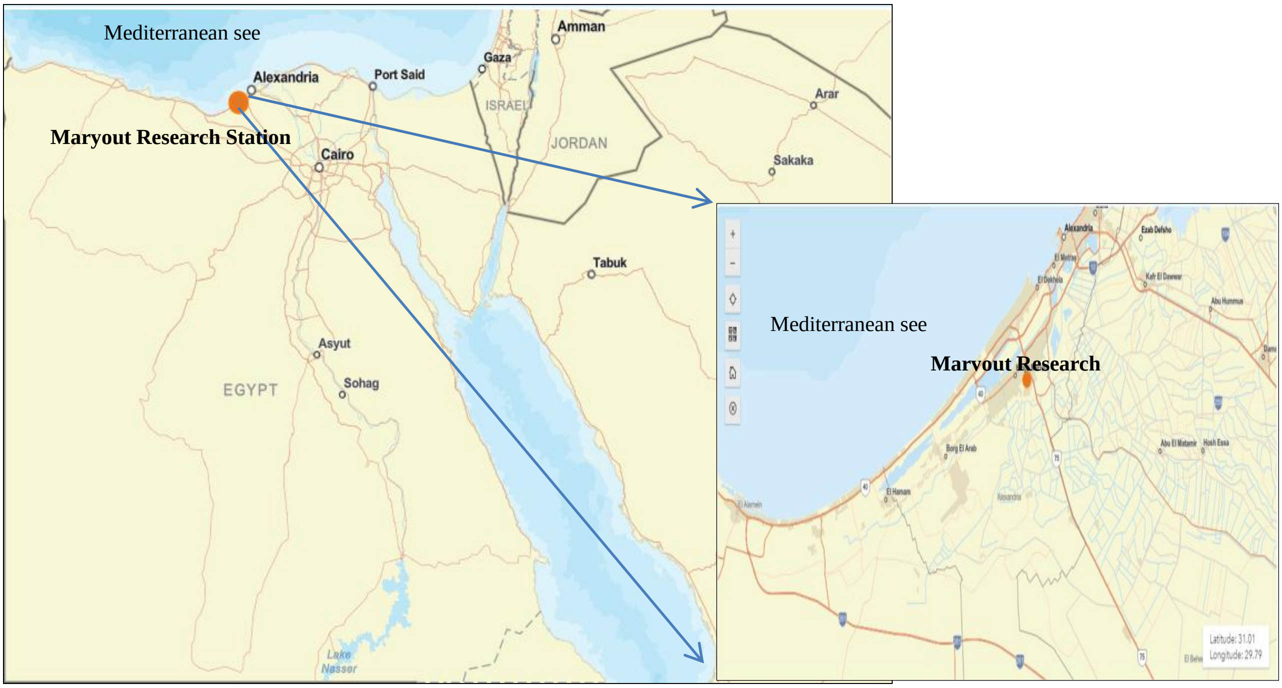
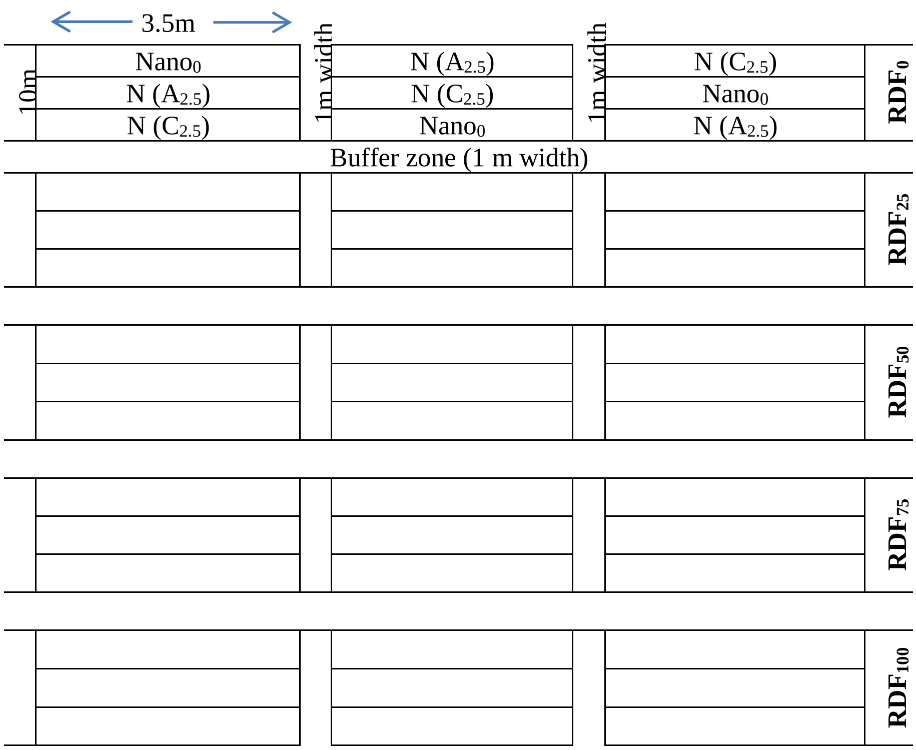


Figure 1. Study location at Maryout research station, Alexandria, Egypt



Recommended Doses of Fertilizers (0, 25, 50, 75 and 100% RDF)

Nano types and rates Artificial (A) and Commercial (C) by (0 and 2.5 ml/l).

Figure 2. Layout of the experiment

The Central Administration for Seed Production (CASP), Agricultural Research Center, Giza, Egypt, supplied the pearl millet (*Pennisetum glaucuml* Shandaweel 1 cultivar) seeds, to which foliar spray treatments were applied at three doses during the tailoring, elongation, and budding stages. The seeds were physically planted in the soil on August 20, 2022, at a rate of 29 kg/ha. Depending on the crop's growth stages, the experiment was irrigated (flooded) once per week to prevent water stress. Three cuttings of the plants were harvested by hand, just above the ground, and measurements were made of the fresh and dry yield.

Chemical contents of shoot

Following a 72-hour oven drying process at 70℃, the digested dry matter of pearl millet plant shoots was wet digested to measure the percentages of nitrogen, phosphorus, and potassium (Chapman and Pratt, 1982). The Microkjeldahl method was used to estimate the total amount of nitrogen, a spectrophotometer was used to determine the phosphorus content, a flame photometer was used to determine the potassium percentage, and a factor based on the nitrogen content of the dry matter was used to compute the crude protein (CP) content (%) (A.O.A.C, 1970), using the equation as following:

Equation 1 CP (%) = Nitrogen (%) × 5.75

Dry matter (DM) content (%) was determined by the following formula, (A.O.A.C., 1970):

Equation 2 DM (%) = DFY/FFY× 100

Where,

DMY= Dry Matter Yield (ton fed^{-1}).

FFY= Fresh Forage Yield (ton fed^{-1}).

Starch percent is determined by the following formula, (A.O.A.C., 1970):

Equation 3 Starch (%) = (17.55+ 0.891(DM) - 24.182).

According to Rostamza *et al.* (2011), the internal nutrients use efficiency (IE) was calculated as follows.

Equation 4 IE = DFY/Nup (kg DM/kg N uptake).

Where, Nup is the plot's nitrogen uptake (kg ha^{-1}) and DFY is its dry matter yield (kg ha^{-1}).

Measurements

Soil

Potassium chloride (2M) is an effective reagent used for extracting nitrogen from soil samples, facilitating the analysis of nutrient levels. In conjunction with this, a solution of DTPA and ammonium bicarbonate serves to extract available potassium, phosphorus, and various micronutrients from the soil. Following the specified extraction procedure ensures accurate measurement of these essential nutrients, which are crucial for understanding soil fertility and plant health (Carter and Gregorich, 2007).

Pearl millet Yield

At harvest time, assessments were conducted at three intervals 30, 60, and 90 days after sowing (DAS) for the first, second, and third cuts of pearl millet to evaluate fresh and dry forage yields measured in mega grams per hectare (Mg/ha). All plants within each plot were harvested to determine both fresh and dry forage yields, as well as the cumulative yields throughout the growing season.

Statistical Analysis

All the obtained data of the study were tabulated and statistically analysed using Duncan's Multiple Range Test for comparing between means of different treatments according to Gomez and Gomez (1984). All statistical analyses were performed using analysis of variance technique by means of "Statistic 9" computer software package and the means were compared by Duncan's multiple range test.

Table 1. Initial status of some properties of the experimental soil

Soil depth (cm)	Soil Texture	pH	EC (dSm^{-1})	$CaCO_3$ (g kg^{-1})	OM (g kg^{-1})	Available nutrients (mgkg^{-1})			SAR
						N	P	K	
0 - 30	SCL	8.11	1.42	371	9.58	16.3	6.12	28.5	1.41

pH= Acidity; E.C = Electrical conductivity in extract soil (1:5); OM= Total Organic Matter (g kg^{-1}); SCL= Sandy Clay Loam and SAR= Sodium Adsorption Ratio. Index values marginal level of N (40-80 mg kg soil^{-1}), P (4-7 mg kg soil^{-1}) and K (60-120 mg kg soil^{-1}) according to Soltanpour (1991) and Jackson (1973).

Table 2. Chemical analysis data of the applied irrigation water

pH	EC (dSm^{-1})	SAR	TDS (ppm)	Soluble cations (meq l^{-1})				Soluble anions (meq l^{-1})			
				Na^+	Ca^{++}	Mg^{++}	K^+	$CO_3^=$	HCO_3^-	Cl^-	$SO_4^=$
7.6	2.75	5.74	1760	14.3	7.25	5.12	0.91	nil	6.13	11.8	9.57

pH = Acidity; E.C = Electrical conductivity; meq l^{-1}= mille equivalent per Liter, SAR= Sodium Adsorption Ratio and TDS= Total dissolved salt.

Table 3. The prevailing weather conditions during pearl millet life cycle at the experimental farm of Desert Research Centre, Maryout district, Egypt, in 2022 and 2023 season

Month	Air temperature (°F) Max.	Air temperature (°F) Min.	Relative humidity (%)	Wind speed (m sec^{-1})	Solar radiation (MJ m^{-2} day^{-1})
			2022		
Augusts	34.51	23.93	61.44	3.57	28.53
September	33.63	23.03	60.50	3.67	28.70
October	28.99	20.51	64.11	3.35	26.11
November	24.91	16.82	63.22	3.31	22.08
December	22.82	14.33	70.02	3.30	17.19
			2023		
Augusts	35.00	24.37	60.62	3.20	26.15
September	34.80	24.05	60.11	3.17	21.96
October	30.31	21.39	65.56	3.09	16.56
November	27.07	18.05	63.72	2.90	13.01
December	22.71	14.87	72.36	2.88	10.36

The mean weather conditions prevailed during the growth seasons of 2022/23 are presented in Figure (1), which graphical representation that includes various climate-related parameters such as wind speed (WS in km/h), relative humidity (RH in %), minimum temperature (T Min), maximum temperature (T Max), and solar flux.

NPK Nano-fertilizer (A) preparation and characterization

Chitosan (CS), sourced from Sigma-Aldrich, forms the basis of a chitosan-NPK Nano-fertilizer (CS-NPK NF) as outlined by Corradini *et al.* (2010). The process began with dissolving chitosan in a 1% acetic acid solution to achieve a 0.2% w/v aqueous solution. The pH was adjusted to 5.5 using a 0.5 M NaOH solution, followed by the addition of sodium tripolyphosphate (TPP) to facilitate the formation of nanoparticles. To load the nanoparticles with nitrogen, phosphorus, and potassium, NPK was dissolved in the nanoparticle solution and homogenized with Tween 80. High-Resolution Scanning Electron Microscopy (HR-SEM) was conducted to analyze the morphology of the created Nano-composite, and a sonication step was employed to minimize particle aggregation before imaging. This study was carried out at the Central Laboratory of the Desert Research Center (NAMCL).

NPK Nano-fertilizer (C) preparation and characterization

NPK Nano-fertilizers (C) was obtained from Nano FAB Technology Company, 4 Saraya Building, 6 October City, Cairo, Egypt.

Characterization of Nano-composite

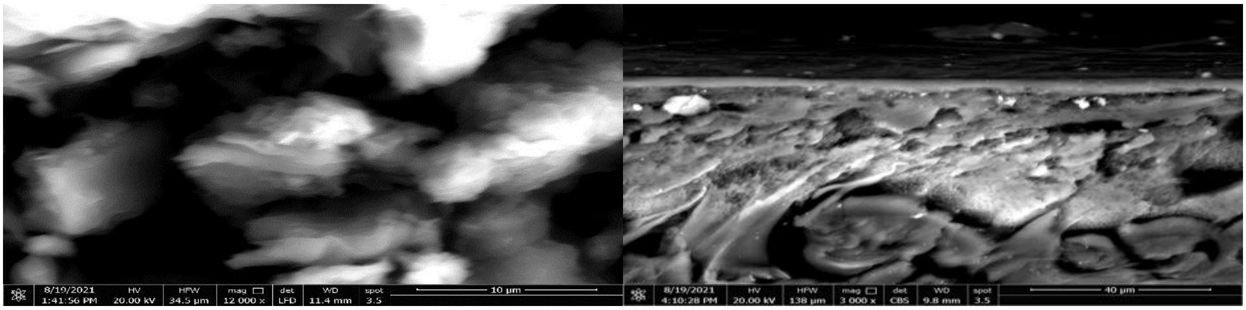
Fourier transform infrared (FTIR) analysis was performed with a resolution of 1 cm^{-1} over a wavelength range of 500–4000 cm^{-1} to identify the presence of specific functional groups in the sample. The dimensions of various nanoparticles were calculated using the Debye-Scherer equation, providing insight into their size distribution. Additionally, the surface characteristics were evaluated through scanning electron microscopy (SEM), allowing for a detailed examination of the nanoparticles' morphology. This combined approach offers a comprehensive understanding of the material's properties and structure.

RESULTS AND DISCUSSIONS

Scanning Electron Microscope (SEM) Analysis

The surface structure and morphology of fertilizer samples were examined using a Hitachi SU3500 Scanning Electron Microscope (SEM). Sample preparation involved placing a small amount of fertilizer on carbon-coated tape, gently compressing it, and mounting it onto the sample stage. To assess the particle size distribution of the nano-NPK (nNPK) powders, dynamic light scattering (DLS) was conducted at a wavelength of 532 nm and a temperature of 25 °C using a 90 Plus Particle Sizer (Brookhaven Instruments). The samples were prepared by dispersing small quantities of the powder in 100% ethanol, followed by ten minutes of sonication. As shown in Figure (3A) (Nano-fertilizer) and Figure (3B) (commercial fertilizer), the SEM analysis revealed significant particle agglomeration in both samples. However, the nano-formulated fertilizer (Figure 3A) exhibited smaller and more uniform particles, with an average diameter ranging from 65 to 95 nm. The DLS analysis also indicated a viscosity of 1.19 cP and a refractive index of 1.36 for the suspension.

(A)



(B)

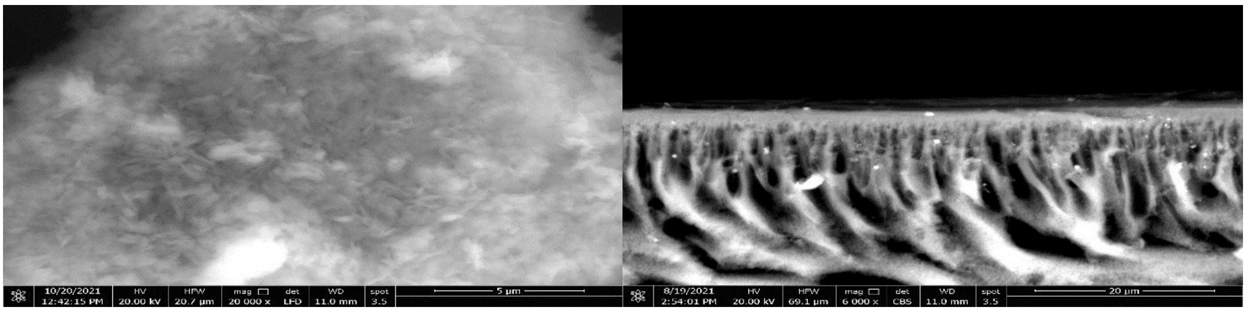


Figure 3. Spectroscopy (SEM) for Nano-artificial (A) and Commercial (B), practical size and cross section

A NEXUS 670 FT-IR spectrometer:

A NEXUS 670 FT-IR spectrometer (Thermo Nicolet, Madison, WI)

Infrared spectra of Nano-powders were recorded by mixing the powders with IR quality potassium bromide (KBr) at a mass ratio of 1:400. The resulting mixture was pressed into a pellet using a 13 mm diameter evacuated die. Spectra were acquired over a range of 400 to 4000 cm^{-1} using a deuterated triglycine sulfate (DTGS) detector and a KBr beam splitter, achieving a resolution of 2 cm^{-1}. To enhance the signal-to-noise ratio, each spectrum was scanned 32 times. The estimated standard uncertainty in wavelength measurement was ± 4 cm^{-1}.

Fourier Transform Infrared Spectrometer (FT-IR) Analysis

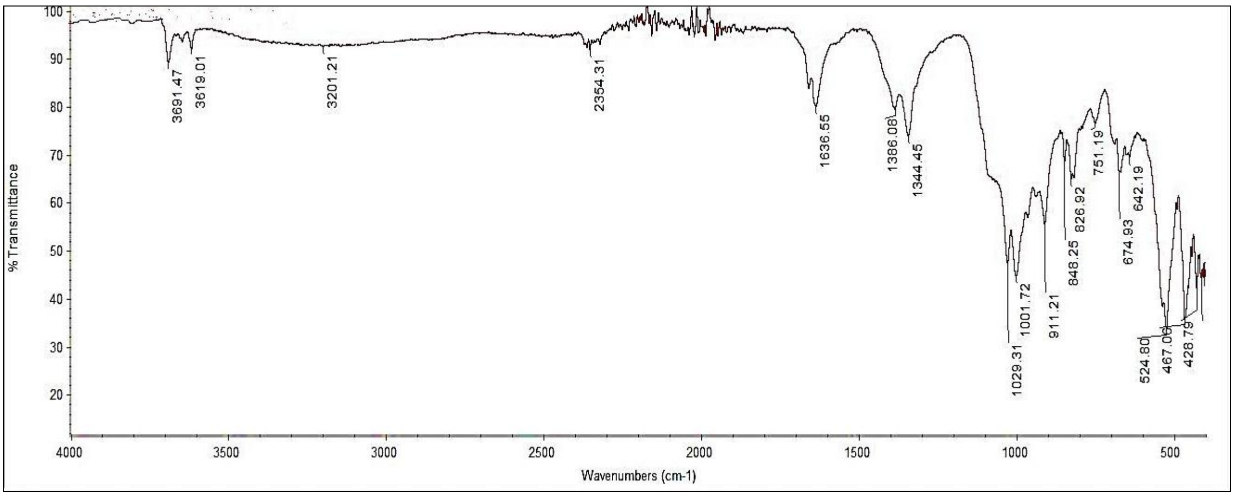
A Fourier Transform Infrared (FT-IR) spectrometer was employed to analyze the functional groups present in the alginate-chitosan carrier and the fertilizer formulation. The FT-IR spectra were analyzed using Spectra-Gryph and Know-It-All informatics software. The original spectrum of the artificial fertilizer revealed the presence of gypsum and mono-calcium phosphate, verified through infrared spectroscopy, with characteristic peaks for various chemical groups identifiable in a corresponding table (Table 4). The spectra indicated specific vibration ranges, such as the OH^- band between 3600 to 2500 cm^{-1} and notable phosphate anion bands at 550, 1065, and 1620 cm^{-1}. Furthermore, the shifts of absorption peaks, including those of carboxyl (-CO) and amide (-NH) groups, were observed in the spectra, indicating interactions within the fertilizer composition. Additional peaks associated with aromatic bonds further characterized the organic components of the fertilizer, underscoring the diverse functional groups identified in the analysis (Shkilnyy *et al.*, 2008).

Figure (4A) displays the FTIR spectrum of the Nano-artificial (A) sample, highlighting several characteristic peaks associated with metal oxide and phosphate-based nanostructures. Sharp peaks at 3691.47 and 3691.01 cm^{-1} correspond to isolated O–H stretching vibrations, likely arising from surface hydroxyl groups on the nanoparticles. A broader band around 3201.21 cm^{-1} suggests the presence of hydrogen-bonded O–H groups or adsorbed moisture. The weak band at 2364.31 cm^{-1} may be attributed to ambient CO_2. Prominent peaks at 1686.55 and 1638.06 cm^{-1} correspond to O–H bending vibrations of water molecules or potential C=O stretching, while the signal at 1394.46 cm^{-1} may indicate carbonate or C–H bending. Strong absorptions at 1029.31 and 1001.72 cm^{-1} reflect P–O stretching, confirming the presence of phosphate groups. Additional bands in the 911.27–751.19 cm^{-1} region are consistent with phosphate or silicate bending modes.

The low-frequency region (674.93 to 428.71 cm^{-1}) exhibits metal–oxygen vibrations, verifying the formation of metal oxide nanoparticles. These spectral features support the classification of the material as an artificial Nano-composite containing phosphate and metal oxide phases, suitable for applications in Nano-agriculture or soil remediation (Takahashi *et al.*, 1983; Plotegher & Ribeiro, 2016 and Anbalagan *et al.*, 2009).

Figure (4B) shows the FT-IR spectrum of the Nano Commercial (C) sample, revealing characteristic functional groups associated with metal oxide-based nanomaterials. A broad absorption band around 3251.56 cm^{-1} corresponds to O–H stretching vibrations, indicating the presence of surface hydroxyl groups or adsorbed moisture. Peaks at 2926.21 cm^{-1} and 1430.14 cm^{-1} are attributed to C–H stretching and bending vibrations, suggesting the presence of residual organic compounds, likely originating from surfactants or stabilizing agents used during nanoparticle synthesis. A distinct band at 1636.44 cm^{-1} further supports the presence of water molecules through O–H bending vibrations. A strong peak at 1074.30 cm^{-1}, along with additional bands at 980.84, 688.3, 609.62, and 545.68 cm^{-1}, corresponds to metal–oxygen and phosphate/silicate vibrational modes. Furthermore, absorption features observed below 500 cm^{-1} are characteristic of metal–oxygen (M–O) bonds, confirming the presence of metal oxide nanoparticles such as ZnO, TiO_2, or Fe_2O_3. These findings collectively confirm the nanostructured composition of the commercial sample and highlight its potential for applications in agricultural or environmental nanotechnology (Lim & Ahmad, 2017; Djamaan *et al.*, 2018 and Nido *et al.*, 2019).

(A)



(B)

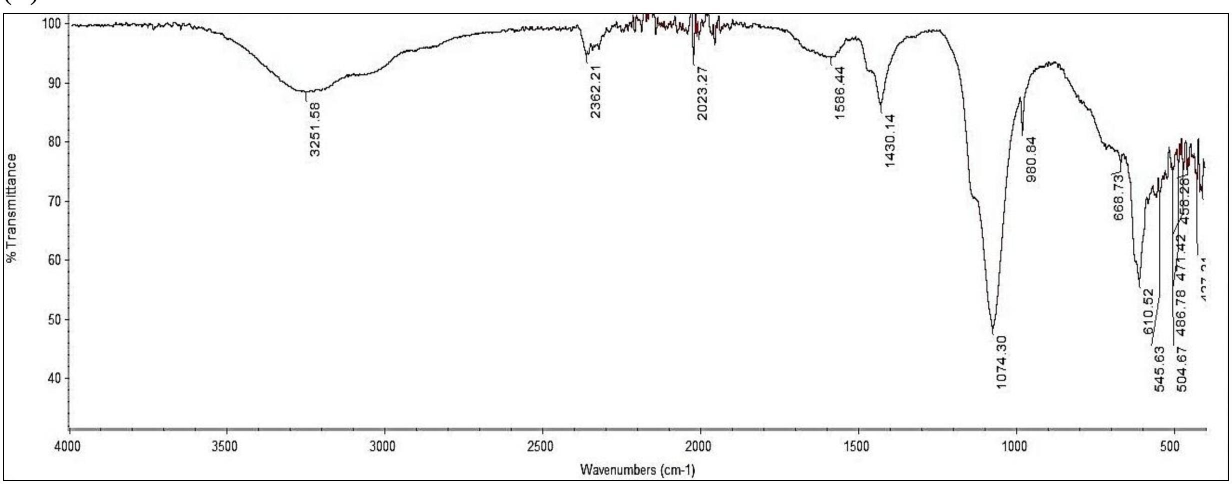


Figure 4. FTIR of Nano-artificial (A) and Commercial (B)

Table 4. IR band assignment

Wave Number (cm^{-1})	Assignment
1642	ν_2, ν_{OH} of H_2O
1240	δ_{oH}- in plane deformation
1158, 1126	PO_2- asymmetric stretching
1010	V_3- (SO_4)
980, 960, 912, 890	$P(OH)_2$- asymmetric stretching
862	γ_{OH}- deformation out of plane
678	V_L, - H_2O vibration mode
662, 612	V_4-(SO_4)
572, 546	PO_2- bending mode
508	PO_2- symmetric deformation in plan
454	V_2- (SO_4)
442	$P(OH)_2$- bending mode

(Takahashi *et al.*,1983 and Anbalagan *et al.*, 2009).

Fresh Foliage Yield

Results in Figure (5) indicate that the application of recommended mineral fertilizers (RDF) alongside Nano-artificial fertilizers (A) can significantly enhance the fresh yield of millet. Specifically, a combination of 75% of the recommended mineral dosages with Nano-artificial fertilizers resulted in the highest recorded fresh forage yield of 105.4 Mg ha^{-1} across three cutting cycles. This treatment not only improved yield in each individual cut but also contributed to a greater cumulative yield over the entire growing season, underscoring the potential benefits of integrating advanced fertilizer technologies in millet cultivation. Fresh forage yield was notably higher at the second cutting compared to the first and third cuttings. The application of mineral fertilizers at increasing rates 25, 50, 75 and 100% of the recommended dose resulted in significant fresh yield increases of 3.57, 41.4, 48.3 and 51.3%, respectively. Additionally, the use of Nano-artificial (A) and commercial (C) foliar applications significantly boosted fresh forage yield by approximately 33.9 and 36.6%, respectively, when compared to a control treatment.

Table (5) displayed that, the significant interaction between fertilization and Nano additives on forage yield. Noticed that, the combination of 75% Recommended Dose of Fertilizer (RDF) and Nano-artificial additive (A) led to a substantial increase in fresh forage yield, achieving 139.5% more than the control treatment. This highlights the promising implications of incorporating Nano technology into agricultural practices, potentially enhancing crop productivity and overall yield efficiency correlating the growth results of forage pearl millet with the characterization of Nano-composites.

Nano-fertilizers represent an innovative advancement in agricultural practices, primarily due to their unique physicochemical properties characterized by a large surface area and a significantly smaller particle size compared to traditional fertilizers. This small particle size enables Nano-fertilizers to traverse plant cellular structures, such as plasmodesmata, facilitating the efficient delivery of vital nutrients directly to sink sites specific locations in the plant where nutrients are stored or utilized for growth. Consequently, the utilization of Nano-fertilizers has shown promise in addressing nutrient deficiencies that can occur in conventional farming systems. In control plots where standard fertilizers are applied or where there is an inadequate application of nutrients, the observed poor nutrient content can often be attributed to a widespread deficiency of essential elements. This deficiency may arise from various factors, including soil degradation, suboptimal fertilization practices, or environmental stressors that limit nutrient availability. Thus, the integration of Nano-fertilizers into agronomic practices not only optimizes nutrient uptake by enhancing bioavailability but also mitigates the risks associated with nutrient loss, ultimately leading to improved plant health and yield. Through ongoing research and development, the potential benefits of Nano-fertilizers may provide a sustainable approach to modern agriculture, addressing both crop production needs and environmental concerns (Abdel-Aziz *et al.,* 2016). A reduction in volatilization, denitrification, leaching, and fixation losses of NPK has been observed by Abdel-Aziz *et al.* (2018) and Yuvaraj & Subramanian (2020). According to Rajonee *et al.* (2016) and Hagab *et al.* (2018).

Figure (6) demonstrates that increasing the recommended dose of fertilizer (RDF) application to 75% with Nano (A) significantly enhances agricultural yields, with fresh yield rising from 48.2 to 115.5 Mg ha[1]. The study employs a second-degree quadratic equation to analyze the interactions between mineral-recommended doses, artificial or commercial Nano types, and their combined effects on fodder yield. Notably, the application of 75% RDF and artificial Nano resulted in substantial yield improvements. This approach not only reduces the reliance on mineral fertilizers, thereby lowering costs and minimizing environmental impact, but it also promotes sustainability, boosts productivity, and enhances soil quality while preserving the environment. These results are in good accordance with those reported by Mahmoud & Swaefy (2020) and Singh *et al.* (2023).

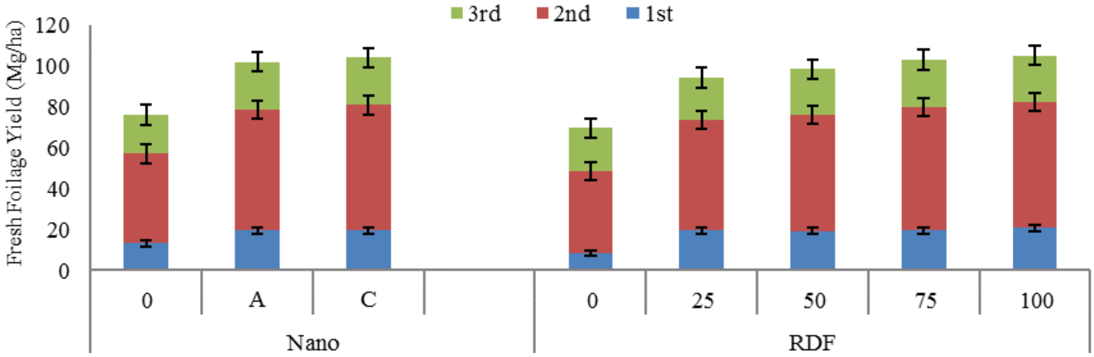


Figure 5. Fresh foliage pearl millet yield as affected by NPK and Nano-fertilizers rates (as average of two seasons)

Table 5. Fresh and dry foliage pearl millet yield as affected by NPK and Nano-fertilizers rates (as average of two seasons)

Treatments		**FFY(Mg ha^{-1})**			
RDF	Nano	1st	2nd	3rd	Accumulation
0	N_0	8.09^{d}	25.40^{e}	14.74^{f}	48.23^{d}
	N_A	8.57^{d}	47.98^{cd}	25.89^{ab}	82.44^{c}
	N_C	8.48^{d}	44.25^{d}	23.00^{abcd}	75.72^{c}
25	N_0	13.87^{c}	45.46^{cd}	19.20^{e}	78.54^{c}
	N_A	21.95^{a}	51.45^{bcd}	20.16^{cde}	93.56^{bc}
	N_C	22.43^{a}	65.64^{ab}	23.35^{abcd}	111.41^{ab}
50	N_0	12.30^{c}	45.88^{cd}	21.32^{cde}	79.50^{c}
	N_A	22.58^{a}	59.18^{abc}	22.54^{bcde}	104.30^{ab}
	N_C	22.68^{a}	65.84^{ab}	23.30^{abcd}	111.82^{ab}
75	N_0	14.93^{bc}	48.41^{cd}	19.89^{de}	83.24^{c}
	N_A	21.50^{a}	67.70^{a}	26.32^{a}	115.52^{a}
	N_C	22.17^{a}	65.44^{ab}	23.39^{abcd}	111.01^{ab}
100	N_0	17.23^{b}	53.78^{abcd}	21.06^{cde}	92.07^{bc}
	N_A	23.18^{a}	66.24^{a}	23.21^{abcd}	112.63^{ab}
	N_C	22.07^{a}	65.77^{ab}	23.62^{abc}	111.47^{ab}
LSD	RDF	2.23	8.01	2.03	11.9
	Nano	1.33	6.77	1.62	9.28
	RDF*Nano	3.29	14.7	3.58	20.7

RDF: Recommended doses Fertilizer as (0, 25, 50, 75 and 100%), N_A: Artificial Nano fertilizer, N_C: Commercial Nano Fertilizer as (0 and 2.5 ml L^{-1}), Cuts of number as 1st, 2nd and 3rd. Values with a common letter are not significantly different using LSD at the 5% level.

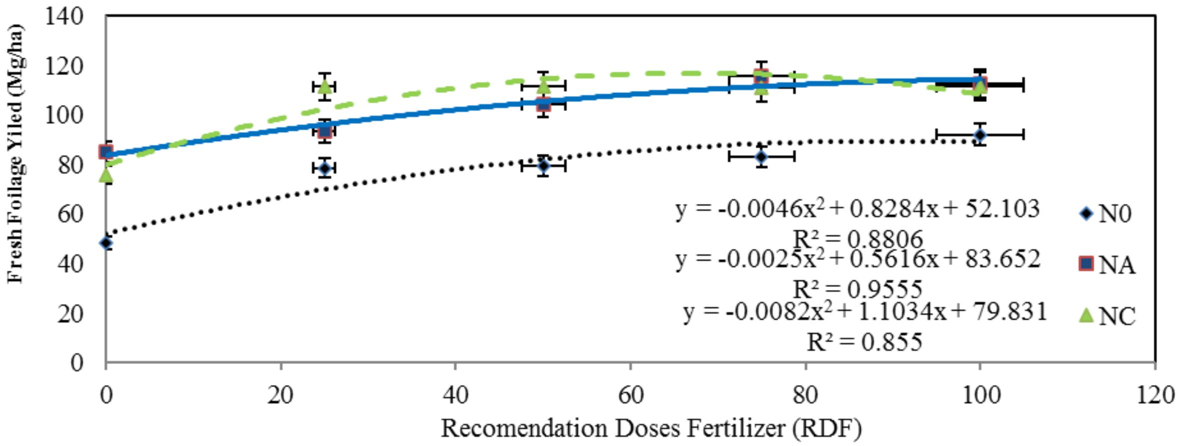


Figure 6. Accumulation fresh foliage pearl millet yield through all cuts as affected by NPK and Nano-fertilizers rates (as average of two seasons)

Nanotechnology presents a promising approach in the agricultural sector, particularly through the use of Nano fertilizers. Research shows that these fertilizers, such as Nano-zeolite loaded nitrogen and Nano-NPK mixtures, significantly enhance plant performance under stress conditions. They contribute to improved vegetative growth metrics, including plant height, number of branches, yield, and overall health indices. Additionally, Nano-fertilizers have been found to boost photosynthetic rates, stomata conductance, carbon dioxide concentration, water use efficiency, and relative water content, thereby promoting better crop resilience and productivity (Mahmoud and Swaefy, 2020). Mahmoud *et al.* (2024) found that adding Nano-amendments to the soil at different rates led to increased tomato plant growth as a result of increased phytochemicals and decreased total number of root-knot nematodes on it.

Concentration of nutrients

The findings illustrated in Figure (7) demonstrate that the combination of recommended mineral fertilizers (RDF) with Nano-artificial fertilizers (A) significantly improves nutrient absorption in millet cultivation. Specifically, applying 75% of the recommended mineral dosage combined with Nano-fertilizers resulted in the highest average nutrient content, recording 2.80% nitrogen, 0.21% phosphorus, and 2.12% potassium across three cuttings. This strategic fertilization approach not only led to enhanced yields in each cutting but also contributed to an increased cumulative yield throughout the growing season. Interestingly, the nitrogen concentration peaked in the third cutting, while phosphorus and potassium levels were notably higher in the first cutting compared to second and the third one. These results highlight the efficacy of advanced fertilizer technologies in fostering healthier plant growth and boosting overall millet productivity.

The application of mineral fertilizers at varying rates 25, 50, 75 and 100% of the recommended dose has shown a significant impact on nutrient content in plants. Increases in nitrogen content were observed at rates of 6.58, 3.07, 5.70 and 7.46%, corresponding to the incremental doses. For phosphorus, the increases were 6.25, 6.25, 18.7 and 12.5%, indicating a more pronounced response at the higher application rates. Potassium content showed smaller but notable increases of 6.08, 0, 2.21 and 3.31%. Furthermore, the utilization of foliar applications, both Nano-artificial (A) and commercial (C), led to substantial enhancements in nutrient uptake. Specifically, nitrogen levels rose by approximately 18.2 and 20.0%, while phosphorus saw increases of 11.8 and 17.6%, and potassium improved by 7.78 and 11.1%, respectively, when compared to a control treatment. This data underscores the importance of both mineral fertilizers and innovative foliar applications in optimizing plant nutrient availability.

Table (6) observed that the significant interaction between fertilization and Nano additives concerning nutrient content in plant growth. The results indicate that the application of 75% of the recommended dose of fertilizer (RDF) in conjunction with Nano-artificial additive (A) resulted in a marked enhancement of key macronutrients. The effects of nutrient additives on plant growth, significant increases in essential nutrient levels were observed. Specifically, nitrogen (N) levels rose by 53.8%, phosphorus (P) levels increased by 50.0%, and potassium (K) levels elevated by 42.3% compared to the control treatment that did not include these additives. These findings highlight the effectiveness of nutrient supplementation in enhancing soil fertility and potentially improving plant health and productivity. This data highlights the potential benefits of integrating Nano additives with reduced fertilizer applications, suggesting a more efficient approach to nutrient management in agricultural practices. Nano-fertilizers possess a unique characteristic with their large surface area and reduced particle size, allowing them to effectively deliver nutrients to plant sink sites through plasmodesmata. Research indicates that the limited nutrient content in control plots is largely due to inadequate application and widespread deficiencies (Abdel-Aziz *et al.,* 2016). Studies have demonstrated that Nano-fertilizers can significantly reduce nutrient losses from volatilization, denitrification, leaching, and fixation (Abdel-Aziz *et al.,* 2018; Yuvaraj & Subramanian, 2020 and Habib, 2021). This enhanced delivery mechanism increases nutrient absorption and utilization efficiency. As particle size decreases, the specific surface area and particle count per unit area of fertilizers rise, leading to greater interaction opportunities and improved nutrient penetration within plants (Duhan *et al.*, 2017 and Lowry *et al.*, 2019).

We observed significant results with the use of Nano nutrients. Nutrient use efficiency is dependent upon foliage yield, the content of nutrients, and the amount of nutrients applied. Application of 75% NPK with Nano nutrients (N, P and K) increased nutrient use efficiency significantly in comparison to other treatments.

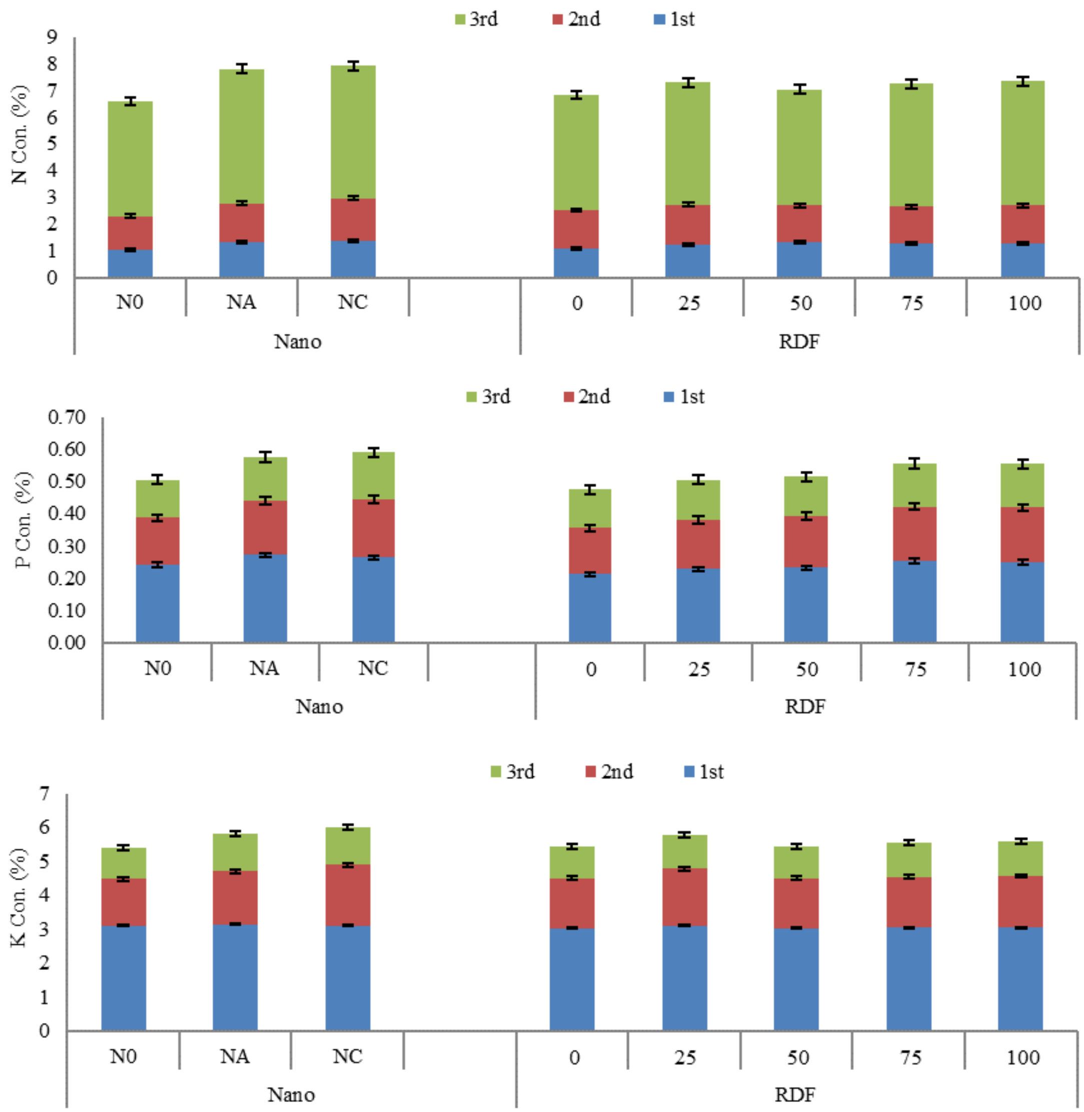


Figure 7. Nitrogen, P and K concentration in foliage pearl millet through all cuts as affected by NPK and Nano-fertilizers rates (as average of two seasons)

Table 6. Nitrogen, P and K concentrations in foliage pearl millet yield as affected by NPK and Nano-fertilizers rates (as average of two seasons)

Treatments		N (%)				P (%)				K (%)			
RDF	**Nano**	**1st**	**2nd**	**3rd**	**Means**	**1st**	**2nd**	**3rd**	**Means**	**1st**	**2nd**	**3rd**	**Means**
0	N_0	0.84^{h}	1.04^{e}	3.57^{g}	1.82^{d}	0.20^{e}	0.12^{f}	0.10^{e}	0.14^{f}	2.91^{c}	0.83^{c}	0.74^{c}	1.49^{d}
	N_A	1.23^{bcde}	1.57^{ab}	5.00^{abcde}	2.60^{ab}	0.22^{cde}	0.15^{e}	0.13^{bc}	0.17^{de}	3.13^{bc}	1.89^{a}	1.15^{a}	2.06^{ab}
	N_C	1.21^{cde}	1.66^{a}	4.38^{def}	2.41^{bc}	0.21^{de}	0.16^{cde}	0.12^{cd}	0.17^{ef}	3.04^{bc}	1.70^{ab}	0.93^{b}	1.89^{abc}
25	N_0	1.04^{g}	1.25^{d}	4.33^{ef}	2.21^{c}	0.25^{bcde}	0.15^{e}	0.12^{d}	0.17^{de}	3.15^{bc}	1.41^{ab}	0.91^{b}	1.82^{abc}
	N_A	1.17^{def}	1.25^{d}	4.31^{f}	2.25^{c}	0.24^{bcde}	0.17^{abcd}	0.12^{cd}	0.18^{de}	2.92^{c}	1.28^{bc}	0.93^{b}	1.71^{cd}
	N_C	1.47^{a}	1.59^{ab}	5.13^{abc}	2.73^{a}	0.28^{b}	0.17^{abc}	0.16^{a}	0.21^{ab}	3.10^{bc}	1.76^{ab}	1.18^{a}	2.01^{abc}
50	N_0	1.10^{efg}	1.36^{cd}	4.51^{bcdef}	2.32^{bc}	0.24^{bcde}	0.15^{e}	0.12^{cd}	0.17^{de}	3.11^{bc}	1.54^{ab}	0.98^{b}	1.87^{abc}
	N_A	1.36^{ab}	1.49^{bc}	5.03^{abcd}	2.63^{ab}	0.28^{b}	0.18^{abcd}	0.12^{d}	0.19^{abcd}	3.01^{bc}	1.36^{b}	1.00^{b}	1.79^{bcd}
	N_C	1.47^{a}	1.59^{ab}	5.13^{abc}	2.73^{a}	0.28^{b}	0.18^{ab}	0.16^{a}	0.21^{ab}	3.09^{bc}	1.75^{ab}	1.18^{a}	2.01^{abc}
75	N_0	1.06^{fg}	1.28^{d}	4.46^{cdef}	2.27^{c}	0.25^{bcd}	0.15^{de}	0.12^{cd}	0.18^{cde}	3.17^{bc}	1.50^{ab}	0.93^{b}	1.86^{abc}
	N_A	1.33^{bc}	1.39^{cd}	5.67^{a}	2.80^{a}	0.34^{a}	0.16^{de}	0.14^{b}	0.21^{a}	3.61^{a}	1.55^{ab}	1.19^{a}	2.12^{a}
	N_C	1.46^{a}	1.59^{ab}	5.12^{abc}	2.72^{a}	0.27^{b}	0.18^{abc}	0.16^{a}	0.20^{ab}	3.10^{bc}	1.77^{ab}	1.18^{a}	2.02^{abc}
100	N_0	1.13^{defg}	1.37^{cd}	4.62^{bcdef}	2.37^{bc}	0.27^{bc}	0.16^{bcde}	0.13^{cd}	0.18^{bcde}	3.20^{bc}	1.63^{ab}	0.97^{b}	1.93^{abc}
	N_A	1.48^{a}	1.59^{ab}	5.14^{ab}	2.74^{a}	0.28^{b}	0.19^{a}	0.16^{a}	0.21^{ab}	3.07^{bc}	1.74^{ab}	1.18^{a}	2.00^{abc}
	N_C	1.24^{bcd}	1.50^{abc}	4.99^{bcdef}	2.58^{ab}	0.28^{b}	0.19^{a}	0.14^{b}	0.20^{abc}	3.23^{b}	1.91^{a}	1.05^{ab}	2.07^{ab}
LSD	RDF	0.09	0.09	0.37	0.18	0.024	0.014	0.004	0.014	0.14	0.26	0.09	0.16
	Nano	0.06	0.07	0.31	0.14	0.023	0.012	0.002	0.011	0.14	0.24	0.06	0.15
	RDF* Nano	0.14	0.16	0.67	0.32	0.048	0.022	0.005	0.025	0.29	0.51	0.15	0.31

RDF: Recommended doses Fertilizer as (0, 25, 50, 75 and 100%), N_A: Artificial Nano fertilizer, N_C: Commercial Nano Fertilizer as (0, and 2.5 ml L^{-1}), Cuts of number as 1st, 2nd and 3rd. Values with a common letter are not significantly different using LSD at the 5% level.

The large surface area and small particle size of Nano-fertilizers, which are smaller than the pore size of the plant's roots and leaves, may be the reasons for this. This may boost the Nano penetration of fertilizers into the plant from the applied surface and increase absorption and nutrient usage efficiency. As particle size lowers, a fertilizer's specific surface area and particle count per unit area increase, providing Nano-fertilizers with more surface area and interaction chances (Duhan *et al.*, 2017 and Lowry *et al.*, 2019). This leads to increased nutrition utilization efficiency by increasing nutrient penetration and absorption. Nano-nutrients smaller than 100 nm increase plant metabolism by improving fertilizer use, lowering pollutants, and being more environmentally friendly (Liu & Lal, 2015 and Yuvaraj & Subramanian, 2020). Singh *et al.* (2017); Hagab *et al.* (2018) and Qureshi *et al.* (2018) reported similar results.

Accumulation Nutrients

The findings presented in Figure (8) indicate that nitrogen, phosphorus, and potassium uptake in plants peaked during the second cutting, surpassing levels observed in the first and third cuttings. This suggests that advanced fertilizer technologies play a crucial role in enhancing plant growth and improving millet productivity. The study demonstrated that applying mineral fertilizers at varying rates (25, 50, 75, and 100% of the recommended dose) significantly influenced nutrient uptake, with nitrogen increases of 10.4 to 39.5%, phosphorus increases ranging from 31.8 to 64.2%, and potassium rising by 14.9 to 48.7% corresponding to higher application rates. Additionally, foliar applications, including both Nano-artificial and commercial methods, have demonstrated significant enhancements in nutrient levels for plants. Compared to control treatments, nitrogen levels increased by approximately 25.1 to 35.3%, phosphorus levels rose by 27.8 to 38.9%, and potassium levels improved by 23.1 to 40.8%. This data underscores the effectiveness of these innovative foliar techniques and mineral fertilizers in optimizing nutrient availability, ultimately supporting better plant growth and health.

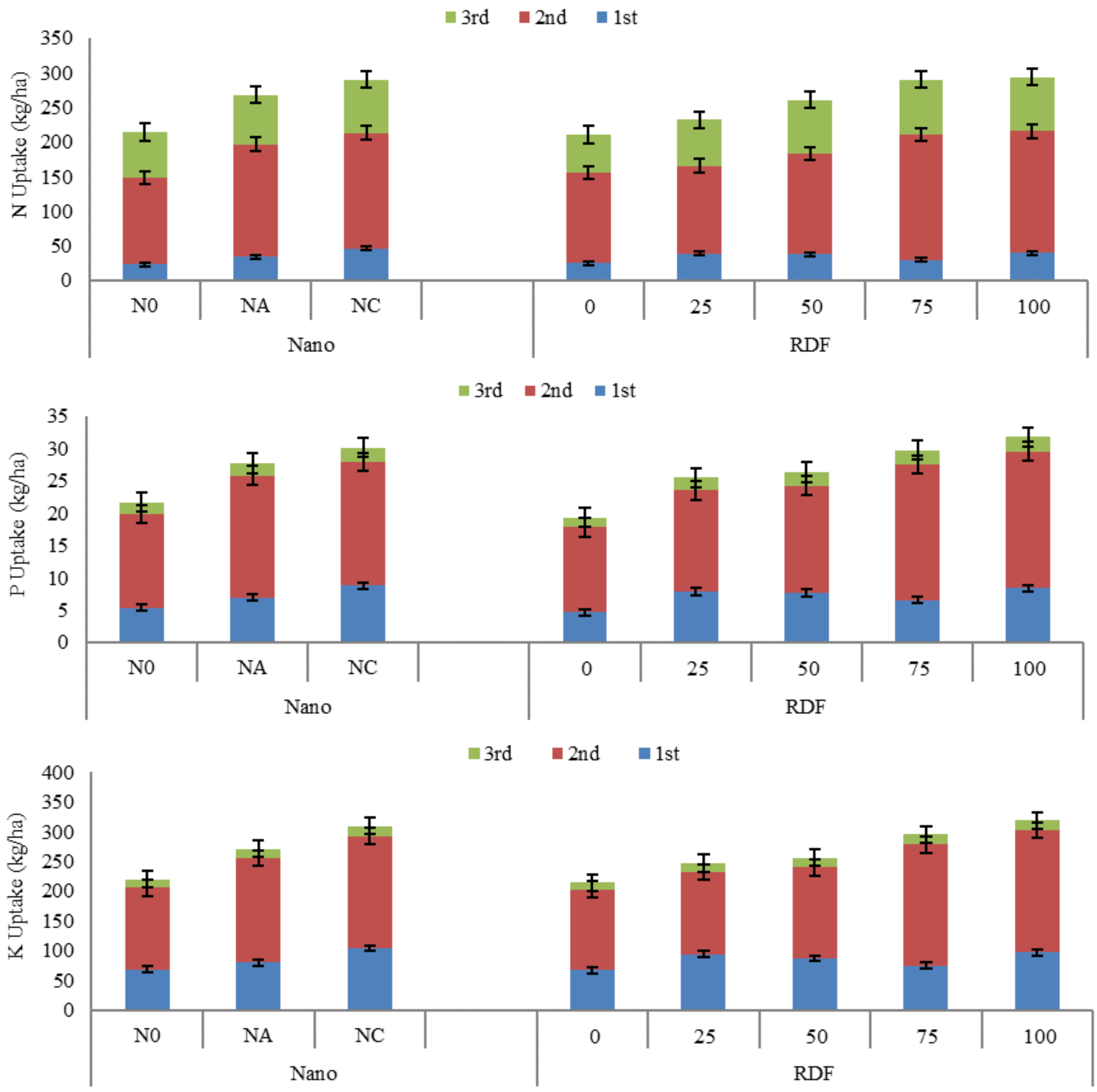


Figure 8. Nitrogen, P and K uptake by foliage pearl millet through all cuts as affected by NPK and Nano-fertilizers rates (as average of two seasons)

Data from Table (7) demonstrate that higher rates of mineral fertilizers, particularly when combined with Nano fertilizers, enhance the accumulation of nitrogen (N), phosphorus (P), and potassium (K) in pearl millet. Specifically, the uptake of N and P peaked at 75% of the recommended mineral dosage combined with Nano-fertilizers, yielding average nutrient contents of 113.3 kg N ha^{-1} and 11.6 kg P ha^{-1}, respectively. Conversely, potassium uptake was maximized at 100% of the recommended mineral fertilizer rate, achieving 117.2 kg K ha^{-1} across three cuttings.

The application of higher rates of mineral fertilizers, especially when complemented by Nano-fertilizers, significantly improves the accumulation of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) in pearl millet. This enhancement in nutrient uptake is critical for optimizing plant growth and yield. Specifically, the research indicates that the uptake of nitrogen and phosphorus reaches when the mineral fertilizer is applied at 75% of the recommended dosage in conjunction with Nano-fertilizers, resulting in impressive average nutrient contents of 120.8 and 132.8 percent. These findings suggest that a strategic approach to fertilizer application can lead to substantial increases in nutrient availability, which are crucial for the robust development of pearl millet. In contrast, the absorption of potassium is found to be maximized at a 100% application rate of the recommended mineral fertilizers, achieving an impressive 169.4 percent across three consecutive cuttings. This differential response underscores the importance of optimizing nutrient management practices to ensure that each nutrient is delivered in the most effective amounts, tailored to the specific crop requirements and growth stages. Overall, these results highlight the synergistic potential of mineral and Nano-fertilizers in enhancing nutrient uptake, thereby contributing to improved agricultural productivity and sustainability in pearl millet cultivation. These results are in good accordance with those reported by Mahmoud & Swaefy (2020); Singh *et al.* (2023) and El-Sharkawy *et al.* (2024).

This may boost the Nano penetration of fertilizers into the plant from the applied surface and increase absorption and nutrient usage efficiency. As particle size lowers, a fertilizer's specific surface area and particle count per unit area increase, providing Nano-fertilizers with more surface area and interaction chances (Duhan *et al.*, 2017 and Lowry *et al.*, 2019). This leads to increased nutrition utilization efficiency by increasing nutrient penetration and absorption. Nano-nutrients smaller than 100 nm increase plant metabolism by improving fertilizer use, lowering pollutants, and being more environmentally friendly (Liu & Lal, 2015 and Yuvaraj & Subramanian, 2020). Singh *et al.* (2017); Hagab *et al.* (2018) and Qureshi *et al.* (2018) reported similar results.

Nutrient use efficiency

The findings presented in Figure (9) reveal important insights into the internal utilization efficiencies of nitrogen (N), phosphorus (P), and potassium (K) in plants, which are crucial nutrients for growth and development.

Table 7. Nitrogen, P and K uptake by foliage pearl millet yield as affected by NPK and Nano-fertilizers rates (as average of two seasons)

Treatments		N (kg ha^{-1})				P (kg ha^{-1})				K (kg ha^{-1})			
RDF	**Nano**	**1st**	**2nd**	**3rd**	**Means.**	**1st**	**2nd**	**3rd**	**Mea**	**1st**	**2nd**	**3rd**	**Means**
0	N_0	13.6^{f}	91.9^{f}	48.2^{e}	51.3^{f}	3.26^{e}	10.3^{d}	1.41^{g}	4.99^{g}	47.3^{g}	73.3^{e}	9.95^{e}	43.5^{f}
	N_A	18.6^{ef}	146.9^{c}	56.4^{de}	73.9^{de}	3.40^{e}	14.2^{c}	1.46^{g}	6.35^{f}	47.5^{g}	177.4^{bc}	13.0^{de}	79.3^{e}
	N_C	42.3^{bc}	152.8^{c}	61.1^{cde}	85.4^{cd}	7.41^{bc}	14.9^{bc}	1.71^{fg}	8.02^{de}	106.7^{a}	156.8^{cd}	13.0^{de}	92.2^{cde}
25	N_0	23.6^{de}	119.1^{e}	68.6^{cd}	70.4^{e}	5.64^{cd}	14.0^{c}	1.87^{de}	7.18^{ef}	71.5^{def}	134.6^{cd}	14.4^{d}	73.4^{e}
	N_A	41.7^{bc}	113.9^{e}	60.8^{cde}	72.1^{e}	8.39^{ab}	16.0^{bc}	1.76^{ef}	8.72^{cd}	103.9^{ab}	116.4^{de}	13.1^{de}	77.8^{e}
	N_C	51.1^{a}	147.4^{c}	71.3^{bcd}	89.9^{c}	9.58^{a}	17.0^{b}	2.19^{bc}	9.60^{bc}	107.8^{a}	163.4^{cd}	16.4^{abcd}	95.9^{bcde}
50	N_0	22.3^{de}	141.3^{cd}	63.8^{cde}	75.8^{de}	4.85^{de}	15.5^{bc}	1.73^{fg}	7.37^{ef}	63.2^{efg}	160.1^{cd}	13.9^{de}	79.1^{e}
	N_A	41.9^{bc}	145.9^{cd}	97.7^{a}	95.2^{bc}	8.63^{ab}	17.2^{b}	2.29^{bc}	9.36^{bc}	92.7^{abc}	133.5^{cd}	19.5^{ab}	81.8^{de}
	N_C	50.9^{a}	148.3^{c}	71.9^{bcd}	90.0^{c}	9.54^{a}	17.2^{b}	2.19^{bc}	9.65^{bc}	106.8^{a}	163.8^{c}	16.3^{bcd}	95.6^{bcde}
75	N_0	25.5^{de}	127.6^{de}	72.4^{bcd}	75.1^{de}	6.13^{cd}	15.3^{bc}	1.95^{cd}	7.81^{de}	75.4^{cde}	148.4^{cd}	15.1^{cd}	79.6^{de}
	N_A	19.9^{ef}	208.5^{a}	76.3^{bc}	101.6^{ab}	5.04^{de}	24.1^{a}	1.88^{de}	10.3^{ab}	54.1^{fg}	232.5^{a}	16.0^{bcd}	100.9^{abcd}
	N_C	45.4^{ab}	205.1^{a}	89.4^{ab}	113.3^{a}	8.52^{ab}	23.6^{a}	2.74^{a}	11.6^{a}	96.4^{ab}	228.6^{a}	20.5^{a}	115.1^{ab}
100	N_0	30.4^{d}	145.2^{cd}	78.6^{abc}	84.7^{cd}	7.20^{bc}	17.3^{b}	2.12^{bc}	8.88^{cd}	85.7^{bcd}	170.7^{bc}	16.6^{abcd}	90.9^{cde}
	N_A	48.9^{ab}	198.3^{ab}	65.9^{cde}	104.4^{ab}	9.17^{ab}	23.2^{a}	2.04^{cd}	11.5^{a}	101.7^{ab}	217.6^{ab}	15.1^{cd}	111.5^{abc}
	N_C	39.8^{c}	184.2^{b}	90.4^{ab}	104.8^{ab}	8.95^{ab}	22.9^{a}	2.43^{ab}	11.4^{a}	103.2^{ab}	229.3^{a}	19.0^{abc}	117.2^{a}
LSD	RDF	4.74	9.59	10.0	5.33	1.10	1.29	0.21	0.72	8.19	18.9	2.27	8.84
	Nano	3.61	8.87	9.36	5.36	0.98	1.11	0.17	0.59	9.15	22.2	1.94	10.1
	RDF* Nano	8.11	18.8	19.8	11.1	2.09	2.40	0.37	1.29	18.6	44.7	4.20	20.5

RDF: Recommended doses Fertilizer as (0, 25, 50, 75 and 100%), N_A: Artificial Nano fertilizer, N_C: Commercial Nano Fertilizer as (0, and 2.5 ml L^{-1}), Cuts of number as 1st, 2nd and 3rd. Values with a common letter are not significantly different using LSD at the 5% level.

Understanding how these elements are utilized through different growth stages can inform agricultural practices and improve crop yields. Specifically, the internal nitrogen utilization efficiency in plants reached its peak during the first cutting. This suggests that plants are more adept at using nitrogen early in their growth cycle, likely due to favorable conditions that support vigorous growth and nutrient uptake. In subsequent cuttings, levels of nitrogen efficiency decline, potentially indicating depletion of readily available nitrogen or a shift in the plant's focus from nitrogen uptake to other growth processes, such as the development of reproductive structures. In contrast, the internal utilization efficiency for phosphorus and potassium did not peak until the third cutting. This delayed efficiency can be attributed to the fact that phosphorus and potassium play critical roles later in plant development, particularly during the flowering and fruiting stages. The increased efficiency during the third cutting suggests that plants may become more effective at utilizing these nutrients when their physiological needs shift, demonstrating an adaptive response to changing growth stages.

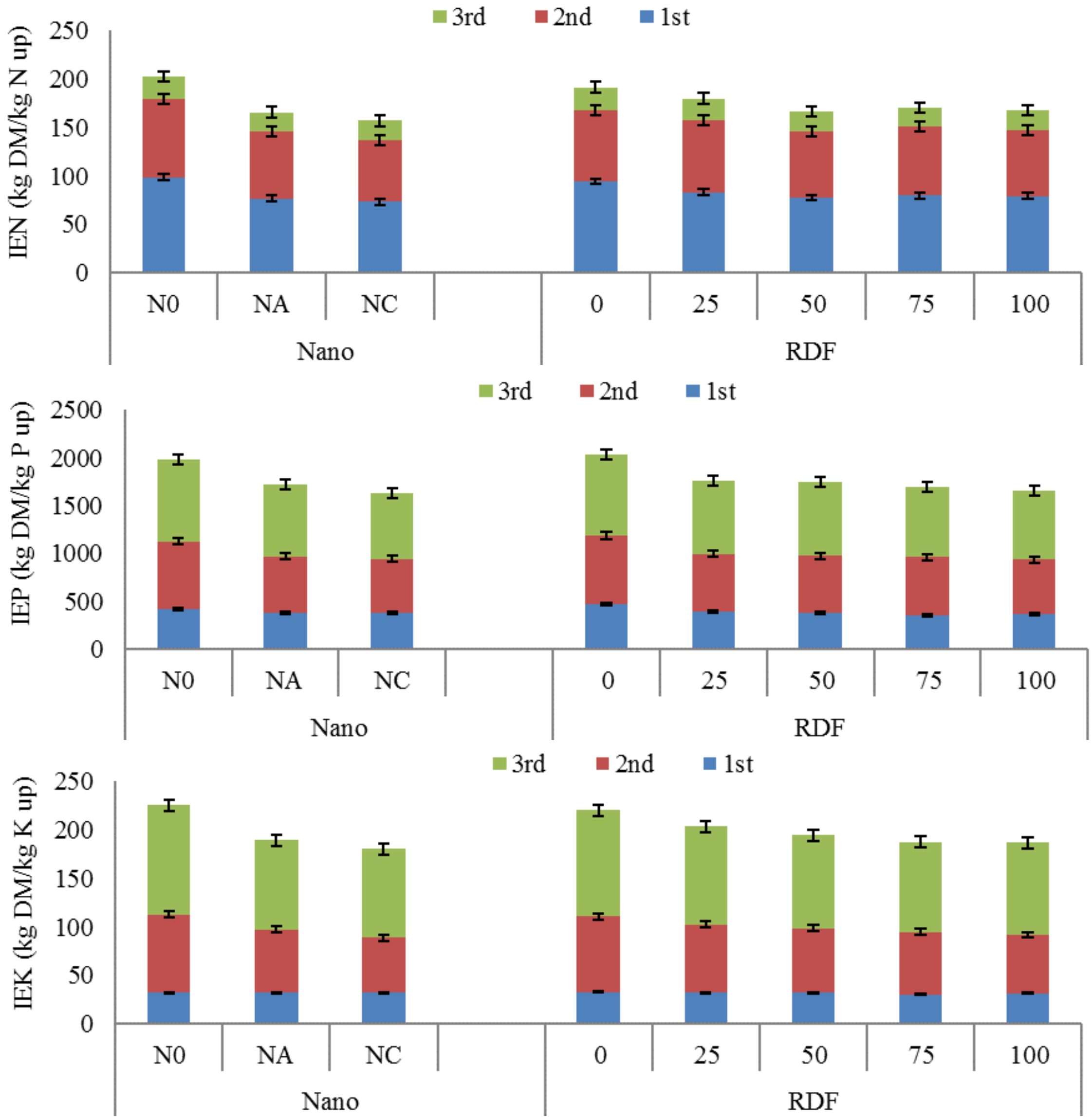


Figure 9. N, P and K internal use efficiency (IE) as affected by NPK and Nano-fertilizers rates (as average of two seasons)

Results indicate significant declines in the Internal Efficiency of Nutrients for various key elements utilized in agriculture, specifically nitrogen (IEN), phosphorus (IEP), and potassium (IEK). The IEN has experienced a decline ranging from 6.50 to 14.2%, while the IEP has seen reductions between 15.8 to 22.8%, and the IEK has dropped by 8.21 to 17.9%. These declines underscore the challenges faced in nutrient management within agricultural systems. However, despite these reductions in internal nutrient efficiency, the application of both Nano-artificial and commercial fertilizers through foliar methods has emerged as a promising solution for enhancing the overall nutrient levels in plants. A comparative analysis has demonstrated substantial decreases in IEN, with declines of approximately 22.4 and 29.4%. Similarly, the IEP and IEK have also reflected significant reductions, with respective declines of 14.8 and 20.8% for IEP, and 18.9 and 25.0% for IEK. Notably, foliar treatments which involve applying nutrient solutions directly onto the leaves have been shown to significantly improve nutrient absorption, thereby contributing to a reduction in nutrient loss ratios. This innovative application strategy enhances plant nutrition by delivering essential minerals and compounds directly to the foliage, allowing for rapid absorption through the leaf surface, which is a technique that helps bypass some of the limitations associated with traditional soil applications. Nutrient availability in soil can be influenced by various factors, including soil pH, moisture levels, and microbial activity, which complicates the efficiency of soil-applied fertilizers. By improving nutrient utilization at the leaf level, these foliar treatments not only promote healthier plant growth but also enhance overall photosynthetic efficiency and crop yield. Importantly, the reduction in nutrient losses associated with foliar applications carries significant implications for sustainable agriculture, as it can lead to lower input costs and a decreased environmental footprint through reduced runoff and leaching of fertilizers into surrounding ecosystems. This dual advantage of improved agricultural productivity alongside environmental stewardship positions foliar treatment as a compelling strategy within modern agricultural practices, aimed at achieving food security in a manner that is ecologically responsible and sustainable.

In crop production systems, nutrient use efficiency indices play a crucial role in evaluating a crop's capacity to absorb and utilize nutrients, thereby influencing biological yields (Fageria *et al.*, 2008). Enhancing nutrients (NPK) use efficiency is particularly important, as it can mitigate the adverse environmental effects associated with mineral fertilizer application (Abbasi *et al.*, 2012 and Singh, 2018). The study's calcareous soil, characterized by a $CaCO_3$ content of 371 g kg (Table 1), contributes to significant ammonia (NH_3-N) losses from applied N fertilizers, further complicating efficiency (Larsen & Gunary, 1962; Terman & Hunt, 1964 and Ali & Habib, 2022). This phenomenon is primarily attributed to the formation of ammonium carbonate $(NH_4)_2CO_3$, which readily decomposes and releases NH_3-N, thus highlighting the complex interplay between soil chemistry and nutrient management strategies (Balba, 1995). Also, phosphorus tends to react with calcium to form less soluble compounds, such as calcium phosphates. This reaction significantly reduces the availability of phosphorus to plants, especially as soil pH rises above 7.5, where the solubility of phosphate ions decreases sharply (Mahdi *et al.*, 2024) The formation of strong bonds between phosphorus and calcium compounds limits its accessibility, leading to symptoms of deficiency in crops (Baccari and Krouma, 2023). The high pH levels typical of calcareous soils exacerbate phosphorus fixation. Optimal phosphorus availability occurs at a pH around 6.5; however, as pH increases into the alkaline range, phosphorus solubility declines further due to precipitation reactions with calcium. This results in poor fertilizer efficiency and necessitates careful management strategies to enhance phosphorus availability. Moreover, the presence of calcium and magnesium in calcareous soils can also affect potassium availability. While potassium is generally more mobile than phosphorus, its uptake can be hindered by high levels of competing cations like calcium and magnesium**.** Nutrient Interactions: The interaction between potassium and other nutrients is critical in calcareous soils. High calcium levels can lead to nutrient imbalances, where potassium uptake may be suppressed due to competition with calcium for plant uptake sites (Akanji *et al.*, 2022). Research indicates that while increasing NPK fertilizer rates generally leads to decreased NPK use efficiency indices, optimal yields may still require higher rates. Specifically, the current study observed that the highest forage yields were achieved with 75% recommended dose of fertilizers (RDF) in conjunction with Nano-fertilizers, and 100% RDF at similar treatments (Table 5).

Biochemical contents

Table (8) findings have revealed significant alterations in biochemical parameters of pearl millet, specifically in crude protein (CP), dry matter (DM), and starch content. Notably, the dry matter content has experienced a marked decline from 41.2% to 38.6%. Concurrently, starch levels have also witnessed a dramatic decrease, with values dropping from 61.3% to 56.9%.

Table 8. Crud protein, dry matter and starch content for foliage pearl millet as affected by NPK and Nano-fertilizers rates (as average of two seasons)

	CP (%)				DM (%)				Starch (%)			
	1st	2nd	3rd	Means	1st	2nd	3rd	Means	1st	2nd	3rd	Means
Nano												
N_0	5.94c	7.23c	24.7b	12.6b	16.9b	24.9a	8.05a	16.6a	11.1b	18.15a	3.18a	10.8a
N_A	7.56b	8.38b	28.9a	14.9a	13.8c	19.0b	6.12c	12.9c	8.26c	12.9b	1.46c	7.54c
N_C	7.88a	9.11a	28.5a	15.2a	20.1a	17.7b	6.60b	14.8b	13.9a	11.8b	1.89b	9.19b
RDF												
0	6.28b	8.17ab	24.8c	13.1c	26.4a	25.1a	6.53b	19.3a	19.5a	18.4a	1.82b	13.2a
25	7.05a	7.84b	26.4bc	13.8bc	16.0b	18.0b	7.06a	13.7b	10.3b	12.0b	2.29a	8.21b
50	7.53a	8.50a	28.1ab	14.7ab	15.1b	18.0b	7.10a	13.4b	9.50b	12.0b	2.33a	7.95c
75	7.38a	8.17ab	29.3a	14.9a	12.4c	21.3ab	6.90ab	13.5b	7.02c	15.0ab	2.15ab	8.06b
100	7.39a	8.54a	28.3ab	14.7ab	14.8b	20.1b	7.04a	13.9b	9.16b	13.9b	2.28a	8.44b
LSD												
Nano	0.32	0.41	1.80	0.81	1.02	3.07	0.35	1.21	0.91	2.73	0.32	1.08
RDF	0.53	0.53	2.11	0.98	1.81	4.13	0.49	1.91	1.62	3.68	0.44	1.70
Nano*RDF	0.78	0.96	3.90	1.78	2.60	6.95	0.82	2.91	2.32	6.19	0.72	2.59

Values with a common letter are not significantly different using LSD at the 5% level.

However, the crude protein content has shown a remarkable increase, rising from 5.12% to 14.1% due to the application of recommended doses of fertilizers (RDF). This suggests that while the overall quantity of certain nutrients may be diminishing, the quality of protein is improving, potentially enhancing the nutritional value of the crop. Furthermore, a comparative analysis involving artificial and commercial Nano-fertilizers has illuminated their effects on the biochemical profile of pearl millet; the incorporation of these fertilizers has led to notable increases in crude protein content of approximately 18.4% and 19.9%, respectively. However, this enhancement in protein levels has come at a significant cost, as dry matter has decreased by 28.4% and 12.2%, alongside starch reductions of around 43.2% and 17.5%. Crude protein (CP) levels in plants notably reached their highest point during the third cutting, exceeding the concentrations found in both the first and second cuttings. In contrast, starch and dry matter (DM) content peaked during the second cutting, surpassing levels recorded in the initial and final cuttings. These findings illustrate the intricate dynamics at play between various fertilizer application methods and their effects on the nutritional composition of pearl millet. This emphasis on CP, starch, and DM underscores the importance of further research into how these fluctuations influence not only crop yield but also the nutritional quality of pearl millet for human consumption and livestock feed. Understanding these relationships is vital for optimizing agricultural practices and promoting the sustainability of food systems, especially in regions where pearl millet is a staple crop.

The analysis of pearl millet forage yield reveals a notable increase in protein content across various treatments compared to the control group, as illustrated in Table (8). This enhancement in protein levels is likely attributed to an accumulation of nitrogen facilitated by these treatments, which is essential for protein synthesis in plants. Specifically, the application of 75% recommended dose of fertilizers (RDF) or the use of Nano-fertilizers has been shown to significantly elevate protein content in pearl millet fodder when contrasted with control conditions. These findings align with previous studies conducted by Singh (2019); Pramanik *et al.* (2020) and Habib (2021) which also observed improvements in protein levels under similar treatment conditions. Such results underscore the importance of nutrient management in optimizing the protein potential of pearl millet, a crucial forage crop.

CONCLUSION

Nutrient management systems play a crucial role in enhancing the foliage production, yield, nutrient use efficiency, and protein content of pearl millet. Research indicates that the application of Nano nutrients, specifically nitrogen, phosphorus, and potassium, significantly boosts crop development by improving nutrient absorption and efficiency. When these nutrients are utilized individually or in combination, they create a conducive environment for optimal growth, resulting in increased nutrient uptake and enhanced overall crop performance. Notably, a treatment that combines 75%

NPK with a specific Nano-artificial (A) has been shown to be both technically effective and financially viable, underscoring the potential of advanced nutrient management strategies in pearl millet cultivation.

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الملخص العربي

تاثير الاسمدة النانونية على بعض صفات النمو، المحصول والتركيب الكيميائى للدخن العلفى فى ارض جيرية

أشرف أحمد محمد حبيب

تلعب الأسمدة دورًا حيويًا في زيادة إنتاج الغذاء، رغم تكلفتها العالية. ومن أجل تحقيق الفوائد المثلى وتقليل فقد العناصر الغذائية، من الضروري تطبيق الكميات والمصادر والتراكيب المناسبة في الأوقات الملائمة وباستخدام الطرق المناسبة. في دراسة تركزت على التربة الكلسية، تم استخدام نوعين من الأسمدة النانوية، الصناعية والتجارية، كرشاشات على الأوراق بمعدلات متفاوتة إلى جانب نسب مختلفة من أسمدة NPK. كشفت النتائج أن تطبيق ٧٥% من الجرعات الموصى بها من الأسمدة، مع الأسمدة النانوية الصناعية، حسّن بشكل ملحوظ إنتاجية الأوراق الطازجة، محققًا أقصى قيمة بلغت ١١٥,٥ ميجا جرام للهكتار الواحد. كما أسفر عن تركيزات أعلى من النيتروجين والفوسفور والبوتاسيوم، بالإضافة إلى محتوى بروتين خام بنسبة ١٦,١%. علاوة على ذلك، أظهر استخدام الأسمدة النانوية التجارية بمعدل ٢,٥ مل لكل لتر من غير الأسمدة المعدنية أعلى نسبة للمادة الجافة (٢٢,٨ %) ومحتوى النشا (١٦,٣%). بشكل عام، تشير الدراسة إلى أن استخدام ٧٥% من الجرعات الموصى بها من الأسمدة مع الأسمدة النانوية الصناعية يعد استراتيجية فعالة لتعزيز كفاءة العناصر الغذائية وإنتاجية التربة في المناطق الجافة.

الكلمات المفتاحية: مصادر المغذيات المتزايدة، تراكم العناصر الغذائية، جودة المحصول، كفاءة المغذيات الداخلية.