

## Ameliorating the response of slow-releasing nitrogen fertilizer on sustainable maize growth

Fatima FEROUZ<sup>1</sup>, Husnain RIAZ<sup>1</sup>, Muhammad AMJID<sup>2,3</sup>, Ali AHMAD<sup>4</sup>,  
Muhammad D. MAJEED<sup>3,5</sup>, Attiq Ur REHMAN<sup>6</sup>, Javed IQBAL<sup>3</sup>  
Sulaiman A. ALHARBI<sup>7</sup>, Mohammad J. ANSARI<sup>8</sup>, Abdul QAYYUM<sup>9\*</sup>

<sup>1</sup>University of Agriculture, Institute of Soil & Environmental Sciences, Faisalabad 38000, Pakistan; [fatimaferoz24@yahoo.com](mailto:fatimaferoz24@yahoo.com); [husnainriaz28@gmail.com](mailto:husnainriaz28@gmail.com)

<sup>2</sup>University of Agriculture, Department of Agronomy, Faisalabad 38000, Pakistan; [amjidm70@gmail.com](mailto:amjidm70@gmail.com)

<sup>3</sup>Barani Agricultural Research Institute, Chakwal 48800, Pakistan; [engrdanish@mail.com](mailto:engrdanish@mail.com); [javid2041@gmail.com](mailto:javid2041@gmail.com)

<sup>4</sup>University of Agriculture, Institute of Horticulture, Faisalabad 38000, Pakistan; [aliabmad16afnj@gmail.com](mailto:aliabmad16afnj@gmail.com)

<sup>5</sup>Soil and Water Conservation Research Institute, Chakwal 48800, Pakistan

<sup>6</sup>Barani Agricultural Research Institute, Centre for Excellence for Olive Research and Training, Chakwal 48800, Pakistan; [aur.attiq@gmail.com](mailto:aur.attiq@gmail.com)

<sup>7</sup>King Saud University, College of Science, Department of Botany and Microbiology, PO Box 2455, Riyadh 11451, Saudi Arabia; [sharbi@ksu.edu.sa](mailto:sharbi@ksu.edu.sa)

<sup>8</sup>Mahatma Jyotiba Phule Rohilkhand University, Hindu College, Department of Botany, Moradabad, Bareilly 244001 India; [mjavedansari@gmail.com](mailto:mjavedansari@gmail.com)

<sup>9</sup>The University of Haripur, Department of Agronomy, Haripur, 22620, Pakistan; [aqayyum@uoh.edu.pk](mailto:aqayyum@uoh.edu.pk) (\*corresponding author)

### Abstract

The extensive utilization of nitrogen (N) fertilizers within maize cultivation systems has resulted in diminished nitrogen use efficiency (NUE) and contributed to nitrogen pollution on a global scale. To assess the ecological repercussions of excessive fertilization, it is imperative to elucidate both the nitrogen use efficiency and the fate of nitrogenous fertilizers upon application. The current research evaluated the potential of a newly developed slow-release nitrogen fertilizer on maize growth and its behavior in soil under controlled conditions. Six different levels of urea fertilizer (UF) and slow-release nitrogen fertilizer (SRNF) were administered within the field, representing 100%, 85%, and 70% of the recommended application rates. The slow-release nitrogen fertilizer (SRNF) exhibited superior performance regarding growth, yield and nutrient retention in comparison to urea fertilizer (UF). Moreover, minimal ammonia emissions were detected with the employment of the slow-release nitrogen fertilizer (SRNF), while other urea-based fertilizers proved inefficient in mitigating ammonia emissions, despite enhancing various growth and yield parameters. The efficiency in nutrient recovery followed a distinct pattern, with polymer-coated fertilizers demonstrating superiority. The plots treated with SRNF displayed significantly higher growth and yield characteristics compared to those treated with urea fertilizer. In terms of NH<sub>3</sub> volatilization, the urea fertilizer (UF) treatment at 100% application rate showed higher emissions (1.99 mg g<sup>-1</sup>) after a 27-day incubation period, as opposed to the slow-release nitrogen fertilizer (SRNF) treatment (1.68 mg g<sup>-1</sup>). Leaching data indicated that urea fertilizer treatments led to greater losses of NO<sub>3</sub>-N (2.01 mg L<sup>-1</sup>) compared to SRNF treatments (0.88 mg L<sup>-1</sup>).

Received: 26 Jan 2024. Received in revised form: 12 Mar 2024. Accepted: 30 Jul 2024. Published online: 20 Aug 2024.

From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

**Keywords:** ammonia emission; biopolymer; coated fertilizers; growth; nitrogen losses; pollution; yield; *Zea mays*

---

## Introduction

Climate change and environmental issues are becoming alarming situation for globe. Environmental pollution poses a particularly formidable challenge due to its broad impact on various life forms (Schwartz *et al.*, 2020). With the increase of global population, the pressure on farmers and food producers to meet growing demands is increasing (Noort *et al.*, 2022). Consequently, the agricultural sector has significantly increased its use of fertilizers to enhance crop yields over recent decades. Since 2015, there has been a yearly rise in the demand for nitrogen, phosphorus, and potassium fertilizers at a rate of 1.9% (Sinha *et al.*, 2020). Chemical fertilizers are now prevalent in all forms of intensive farming, including field crops, vegetable gardens, and ornamental and forestry nurseries (Bisht *et al.*, 2020). This is especially true in Pakistan, where chemical fertilizers play a crucial role in crop production (Khan *et al.*, 2023). Nitrogen fertilization is a proven method to boost and sustain crop yields, with its importance growing as the global population expands and available cropland diminishes, making nitrogen fertilization critical for food security (Su *et al.*, 2023). Unfortunately, over 50% of nitrogen fertilizer is not effectively utilized by crops (Karapatzak *et al.*, 2023). Nitrogen losses through leaching, runoff, and gaseous emissions (such as NH<sub>3</sub>, N<sub>2</sub>O, and NO<sub>x</sub>) pose risks to water and air quality and contribute to global warming (Jeon *et al.*, 2023). Nitrogen-containing fertilizers are widely used due to the vital role of nitrogen in plant growth, but their increasing use has significant environmental repercussions (Powelson *et al.*, 2022). Between 40% to 70% of nitrogen fertilizers are lost to the environment through volatilization, denitrification, or nitrate leaching, further worsening groundwater contamination and surface water quality (Abbasi *et al.*, 2023). Astonishingly, only a small fraction of the nitrogen used in nitrogenous fertilizers makes its way into the human body, whether one follows a vegetarian (14%) or non-vegetarian (4%) diet, from fertilizer manufacturing to the food chain (Yaseen *et al.*, 2023). Inefficient utilization and high nutrient losses, particularly of nitrogen and phosphorus, result in the excessive use of these fertilizers in agriculture to achieve optimal crop yields, with substantial losses occurring through runoff and groundwater systems (Duan *et al.*, 2021).

In recent years, there has been a growing interest in the use of slow-release nitrogen fertilizers (SRNF) as a means to address several environmental and agricultural challenges. Previous studies have explored the potential of SRNF in mitigating groundwater pollution, lowering greenhouse gas emissions, and mitigating the impacts of climate change (Puertas *et al.*, 2023). However, the majority of these inquiries have centered on coatings for fertilizers crafted from materials that are not only costly but also have the potential to damage soil microorganisms, such as sulfur, waxes, polyethylene, and synthetic polymers (Tyagi *et al.*, 2022). An alternative approach that has shown promise is the use of plant-based polymers for fertilizer coatings. These polymers offer a more controlled and eco-friendly release of nutrients into the soil, making them a preferable choice for sustainable agriculture (Sahu *et al.*, 2022). Moreover, such value-added fertilizers not only enhance nutrient uptake by crops but can also provide essential elements like zinc and iron. However, the outcomes of studies examining the application of these value-added fertilizers and their release patterns in the soil have often been inconclusive. Some research has failed to demonstrate clear environmental and agronomic advantages of coated fertilizer technologies in terms of reducing nitrous oxide and ammonia emissions (Ribeiro *et al.*, 2020). Furthermore, these coated fertilizers may not always release nutrients in alignment with the specific needs of plants, creating a potentially stressful environment for the crops (Yaseen *et al.*, 2023). In response to these challenges, recent research has seen extensive application of slow-release nitrogen fertilizers in various crops, including rice, maize, and other field crops, owing to the development of more efficient and eco-friendly

fertilizers (Javed *et al.*, 2022). To optimize the use of slow releasing nitrogenous fertilizer, there has been a particular focus on a blended fertilizer known as UNS (Ultum Nature System), which combines urea with a slow-release nitrogen fertilizer. This approach aims to reduce fertilizer costs while enhancing economic benefits by addressing the issue of slow nutrient release during the early stages of crop growth (Heidari *et al.*, 2022). Ultum nature system not only reduces labor and fertilizer expenses but also ensures a steady supply of nitrogen, minimizes soil nutrient leaching, and ultimately leads to increased crop yields.

Therefore, there is an immediate necessity to assess the effectiveness of these micronutrient-enriched fertilizers when compared to polymer-coated fertilizers across various cropping scenarios, as the efficiency of micronutrients may fluctuate with changes in cultivation practices (Suman *et al.*, 2023). In an effort to enhance the utilization of mineral nutrients and reduce nitrogen losses, this study seeks to evaluate a novel generation of slow-release nitrogen fertilizers that are coated with biodegradable polymers. Agricultural soils typically contain low concentrations of nitrogen, prompting the application of chemical nitrogen fertilizers to meet the demands of crops. Some commonly employed nitrogen fertilizers available in the market include urea, diammonium phosphate (DAP), calcium ammonium nitrate (CAN), and ammonium nitrate (Pajura *et al.*, 2023). The application of nitrogen fertilizers leads to nitrogen loss through various mechanisms, including (i) ammonia volatilization ( $\text{NH}_3$ ), (ii) nitrate leaching ( $\text{NO}_3^-$ ), and (iii) the release of nitrous oxide ( $\text{N}_2\text{O}$ ) and nitrogen dioxide ( $\text{NO}_2$ ) (Qiu *et al.*, 2022). Excessive application of nitrogen fertilizers can result in issues such as poor nitrogen utilization efficiency, environmental pollution, and contributions to global warming (Jiang *et al.*, 2022).

The cultivation of maize (*Zea mays* L.) holds significant importance in global agriculture (Mangani *et al.*, 2019). In Pakistan, maize is cultivated across 1.720 million hectares, with an average yield of 5922 kilograms per hectare, leading to an annual production of 4.3383 million tonnes (GOP, 2023). Maize is favored for its high yield potential, shorter growth cycle, adaptability to various environmental conditions, economic value for both human consumption and livestock feed, making it a cost-effective option for the agriculture and related industries. In this investigation, we examined the effects of Urea and its modified counterparts, specifically slow-release nitrogen fertilizers, on the performance of maize (*Zea mays* L.). The slow-release nitrogen fertilizers variants were subjected to different treatments, involving (i) rinsing with hydrochloric acid (HCl) to eliminate ash, (ii) washing with ethanol to eliminate organic compounds, or (iii) loading with soluble nutrients from maize digestate. The primary objectives of this study were to assess the influence of SRNF and urea on  $\text{NH}_3\text{-N}$  volatilization and  $\text{NO}_3\text{-N}$  leaching and to evaluate their impact on nitrogen uptake and maize growth under field conditions. We posited that the application of value-added and coated fertilizers might result in a trade-off between nutrient utilization efficiency and  $\text{NH}_3$  volatilization. However, the effects on crop performance could vary depending on the specific type and release pattern of the applied fertilizers and the prevailing soil conditions.

## Materials and Methods

The field experiment for maize cultivation involved six distinct treatments:  $T_1 = 100\%$  recommended urea fertilizer (UF),  $T_2 = 85\%$  UF,  $T_3 = 70\%$  UF,  $T_4 = 100\%$  slow-release nitrogen fertilizer (SRNF),  $T_5 = 85\%$  SRNF, and  $T_6 = 70\%$  SRNF. This experiment took place at the agronomy experimental field of the University of Agriculture Faisalabad, Pakistan, from March to June 2022. The area experiences semi-arid climatic conditions characterized by high temperatures, elevated relative humidity, heavy rainfall, and occasional strong winds. The soil's physicochemical properties were assessed in the Soil and Chemistry laboratory at UAF (Table 1). The experiment employed a randomized complete block design with three replications, and the data were analyzed statistically as per Steel *et al.* (1997) guidelines. Recommended doses of NPK and specific fertilizer sources were utilized. The crop received irrigation five times with canal water. In total, there were 18 plots for

each independent experiment, each covering a half-acre area with a size of 12 m<sup>2</sup> for every plot. The maize variety 'DK4622' (Hybrid variety) was sown at a rate of 25 kg ha<sup>-1</sup> on March 19, 2021. Prior to commencing the experiment, soil samples were collected from the field using an auger at a depth of 12 inches for physicochemical analysis, which encompassed various parameters. For each plot, grain and biological yields were recorded. The soil at the experimental site exhibited a sandy clay loam texture with an electrical conductivity of 1.5 dS m<sup>-1</sup> (ECe), a pH of 7.7, an organic matter content of 0.64%, total nitrogen content of 0.04%, Olsen phosphorus of 6.2 mg kg<sup>-1</sup> soil, and extractable potassium of 128 mg kg<sup>-1</sup> soil (Table 1). Chemical Characteristics of Slow-Release Nitrogen Fertilizer (SRNF) was given in (Table 2). The concentrations of various ions, such as Ca<sub>2+</sub> + Mg<sub>2+</sub>, SO<sub>4</sub><sup>2-</sup>, Cl<sup>-</sup>, HCO<sub>3</sub><sup>1-</sup>, CO<sub>3</sub><sup>2-</sup>, and soluble Na<sup>+</sup> in the soil extract, were determined, with their values provided. Moreover, total nitrogen, available phosphorus, and available potassium were assessed using established methods, and their respective concentrations were reported (Table 3). The total productivity of crops was worked out while biological yield was calculated by formula given below:

$$\text{Biological Yield} = \text{Total biomass of plants in plot (grain + straw yield)}$$

The total N in the soil and shoots was measured using the Kjeldahl method (1) nitrogen uptake for each plot was calculated by multiplying the plant N with the dry matter (yield) for each plot, and the N use efficiency of the fertilizers was calculated. Nitrogen use efficiency (NUE) was determined by subtracting the grain yield of control plot from grain yield of fertilized plot and then divided by the amount of fertilizer applied in kilograms (Barber, 1976):

$$\text{NUE} = (\text{Grain yield from fertilized plot} - \text{Grain yield from control plot}) / \text{Amount of fertilizer used (kg)}$$

**Table 1.** Physio chemical properties in soil

Parameter	Unit	Values
Textural class	....	Sandy clay loam
Organic matter	%	0.72
pH (1:5 soil water)	....	7.7
Total nitrogen	%	0.04
Available phosphorous	mg kg <sup>-1</sup>	6.9
Extractable potassium	mg kg <sup>-1</sup>	146

**Table 2.** Chemical characteristics of slow-release nitrogen fertilizer (SRNF)

Sr. No	Parameters	Unit	Value
1	Total nitrogen	%	22
2	Phosphorous	%	2.6
3	Iron	%	0.16
4	Organic carbon	%	17

**Table 3.** Properties of the experimental soil

Treatment	Carbonate (mmol. L <sup>-1</sup> )	Bicarbonate (mmol. L <sup>-1</sup> )	Chloride (mmol. L <sup>-1</sup> )	Ca+Mg (mmol. L <sup>-1</sup> )	pH	EC (ds m <sup>-1</sup> )	O.C (%)	Sodium (mmol. L <sup>-1</sup> )	Potassium (mg kg <sup>-1</sup> )	N in Residual soil (%)
UF	0.70±	8.1±	30±	5.96±	7.96±	2.296±	17.38±	0.01±	0.009±	0.076±
100%	0.11	0.15	2.50	0.18	0.09	0.04	0.26	0.00	0.000	0.00
UF	0.70±	7.2±	18.33±	5±	7.82±	2.21±	17.04±	0.01±	0.006±	0.075±
85%	0.05	0.41	0.44	0.17	0.02	0.04	0.25	0.00	0.00	0.00
UF	0.40±	6.06±	14.73±	4.73±	7.54±	1.88±	16.22±	0.06±	0.004±	0.071±
70%	0.20	0.58	1.268	0.14	0.04	0.03	0.13	0.02	0.00	0.00
SRNF	0.93±	9.7±	44.66±	6.23±	8.03±	2.54±	17.78±	0.015±	0.01±	0.077±
100%	0.17	0.36	1.76	0.14	0.06	0.1	0.15	0.00	0.00	0.00
SRNF	0.66±	7.53±	27.5±	5.63±	7.8±	2.03±	16.63±	0.01±	0.007±	0.072±
85%	0.08	0.31	3.04	0.20	0.06	0.02	0.22	0.00	0.00	0.00
SRNF	0.53±	6.83±	16.33±	4.83±	7.70±	2.02±	16.79±	0.04±	0.005±	0.073±
70%	0.066	0.44	0.60	0.20	0.06	0.04	0.19	0.02	0.00	0.00

\*The data expressed as means ± standard deviation (n = 3). Urea and SRNF represent ammonium nitrate, enriched urea with ammonium nitrate, and modified slow-release nitrogen fertilizers (SRNF), respectively. OC = organic carbon of the soil, OM = organic matter, CO<sub>3</sub><sup>2-</sup> HCO<sub>3</sub><sup>-</sup> = carbonate and bicarbonate in the soil and SRNF, Ca+Mg = calcium and magnesium present in the soil and SRNF.

#### *Measurement of plant chemical parameters*

For the chemical analysis, the wet digestion method was employed to determine the nitrogen and phosphorus content. Nitrogen (N) levels in both grains and straws were assessed using Kjeldahl's method as described by Page *et al.* (1982). In this method, a 10 ml digest solution was placed into the distillation tube, and an additional 10 ml of 40% NaOH was introduced. Simultaneously, 10 ml of 4% boric acid (H<sub>3</sub>BO<sub>3</sub>) was placed in a conical flask, positioned beneath the condenser outlet of the distillation apparatus. The mixture was heated to induce boiling, allowing the resulting vapors to enter the distillation tube containing the sample. Ammonia gas fumes were generated and then directed through the condenser into the 4% boric acid until the boric acid solution became colorless. The resulting distillate was subsequently titrated with standardized 0.01 N H<sub>2</sub>SO<sub>4</sub> until a change in color was observed. The volume of acid used during titration was carefully recorded. The amount of nitrogen was then calculated using the following formula:

$$N (\%) = \frac{(V-B) \times N \times V_1 \times 14.01}{Wt \times V_2 \times 1000} \times 100$$

#### *Preparation of the fertilizer (SRNF)*

The process of manufacturing the slow-release nitrogen fertilizer (SRNF) involved pyrolysis, after which the end product was finely ground into a powder. To create SRNF-coated urea, a pan granulator was employed, which featured an agitator at the top of the pan, capable of stirring the materials as needed. During the granulation process, a liquid binder was sprayed onto the mixture of urea and coating material, enabling the granules' surface to absorb the coating material. The chemical properties of the slow-release nitrogen fertilizer (SRNF) are detailed in Table 2. For crop planting, the seeds were sown on seed beds at a rate of 25 kg per hectare, with row-to-row and plant-to-plant distances maintained at 12 cm and 20 cm, respectively. In the trial sowing, the recommended row-to-row and plant-to-plant distances were observed on ridges. Three levels of urea and SRNF were applied, starting with the full recommended dose of urea at 100%, followed by 85% and 70% doses. The application of SRNF followed a similar pattern. Once the seedlings had been established, a plant-to-plant spacing of approximately 12 cm was maintained through thinning. To prevent competition from weeds, the crop was hoed three times. A total of sixteen irrigations were provided for the crop's water requirements, with the first irrigation taking place seven days after sowing, followed by subsequent irrigations.

#### *NH<sub>3</sub>-N volatilization and column study for NO<sub>3</sub>-N leaching measurement*

To measure NH<sub>3</sub> volatilization, we took 100 grams of soil, which had been amended with either UF or SRNF, and placed it into a 250 ml Schott bottle (respiration jar). Within the Schott bottle, we suspended 20 ml scintillation vials, each containing 10 ml of 0.2 M sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), to capture the NH<sub>3</sub> that volatilized from the soil treatments. The NH<sub>3</sub> collected was quantified by conducting a back titration with 0.4 M sodium hydroxide (NaOH) to determine the amount of unconsumed acid. Throughout the course of the experiment,

maintained one control setup, which involved soil without any treatment. During the initial 9 days, we measured NH<sub>3</sub> volatilization on a daily basis, and then, from day 10 to day 19, we conducted measurements every two days as part of the incubation study. The amount of NH<sub>3</sub> volatilized was calculated by using the following eq.

$$A = \frac{2}{1} X \left\{ Y \times \left( 1 - \frac{D}{C} \right) \times X \right\} X \left( \frac{17}{B} \right)$$

\*where A = NH<sub>3</sub> emission (mg g<sup>-1</sup> soil), B = weight of soil (g), C = volume of NaOH used for blank titration (ml), D = volume of NaOH used for soil titration (ml), Y = volume of H<sub>2</sub>SO<sub>4</sub> used to capture NH<sub>3</sub> emission both in the soil and blank (ml), X = molarity of H<sub>2</sub>SO<sub>4</sub> used to capture NH<sub>3</sub> from the soil (M), and 17 = molecular mass of NH<sub>3</sub> (g mol<sup>-1</sup>).

#### *Column experiment of N leaching*

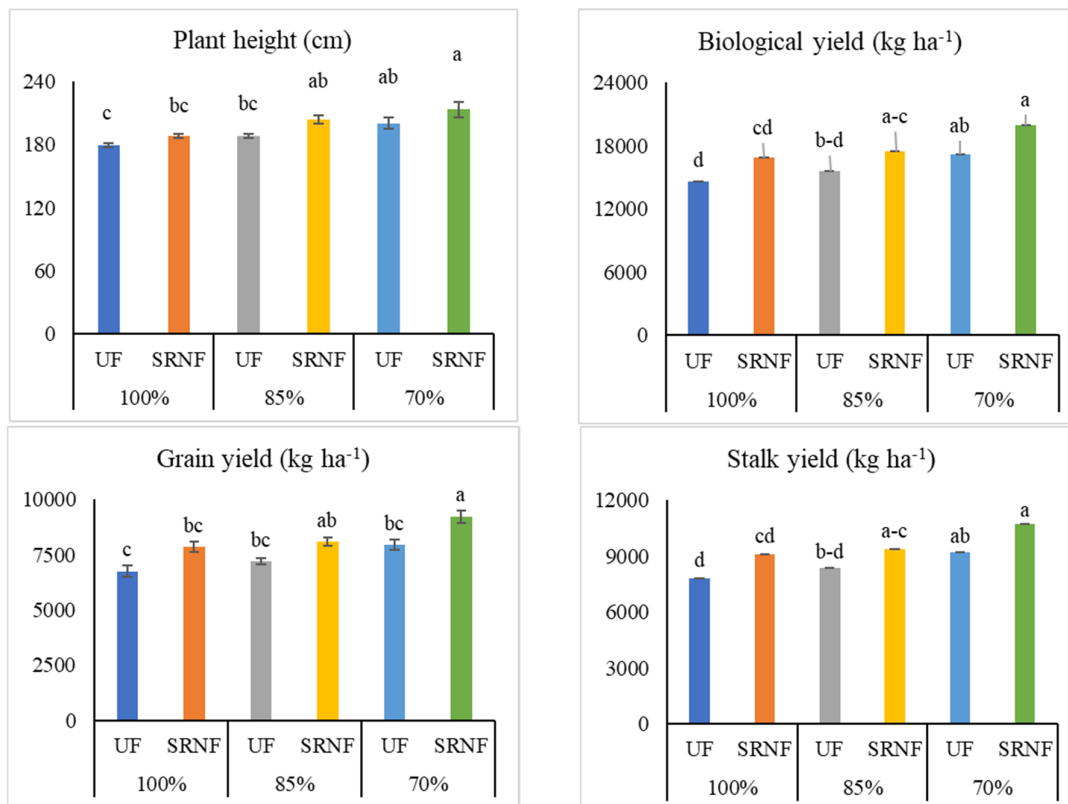
Set up a column experiment to investigate the leaching of nitrogen (N) from UF and SRNF. The experiment involved using a plastic column with a diameter of 5 centimeters and a height of 25 centimeters. At the base of the plastic column, we attached a 100-mesh nylon sheet, which had three small holes to facilitate drainage. Within each column, we evenly distributed 20 grams of acid-washed quartz sand at the bottom, upon which we packed 150 grams of test soil to a height of approximately 10 centimeters before applying the treatments. The experimental treatments consisted of soil with urea fertilizer as a control (UF) at a rate of 0.04 grams per column and soil with slow-release nitrogen fertilizer (SRNF) at a rate of 0.11 grams per column (with the N rate matching that of UF). For each treatment, we carefully weighed the specified amount of test fertilizer and placed it on top of the soil in the column. We then added another 100 grams of soil evenly and finally covered it with an additional 20 grams of quartz sand. Each treatment was conducted in triplicate. Distilled water was introduced into the columns to reach the soil's field capacity, allowing the soil to stabilize for one day before the leaching process began. In the leaching test, the soil within the column was irrigated with distilled water, with each irrigation totaling 100 milliliters, and the flow rate was set at 3.0 milliliters per minute. This irrigation was accomplished using a container regulated by a needle valve positioned at the top of the column. The leaching process was carried out from day 1 to day 14 after the application of the fertilizer, and the resulting leachate was collected in 250-milliliter glass bottles. After each leaching event, all collected leachates were passed through 0.45-micron nylon filters and stored in a dark, temperature-controlled environment at 4°C until they were ready for analysis. For each column, we made daily measurements of leachate water volume, ponding water depth, and evaporation.

A spectrophotometer was utilized to measure the nitrate (NO<sub>3</sub><sup>-1</sup>) levels in the samples. It's worth noting that the samples should contain no more than 2.5 ppm of nitrate-nitrogen (NO<sub>3</sub>-N) but should have more than 2 grams of chloride per liter. In cases where the NO<sub>3</sub><sup>-1</sup> concentrations in samples exceeded the specified limit, they were diluted with 0.1 M HCl. To analyze the samples, we placed 10 ml of each sample into stoppered test tubes and added 0.1 ml of hydrazine sulfate solution. Subsequently, 10 ml of acid, dispensed from a burette with a tap lubricated only with H<sub>2</sub>SO<sub>4</sub>, was added to each test tube. Care was taken to prevent excessive mixing that could cause the solution to boil. The tubes were then sealed and cooled under running water. The absorbance was measured at 410 nm, and the difference between two readings was indicative of the NO<sub>3</sub><sup>-1</sup> concentration. A calibration factor was established by processing samples with a known addition of NO<sub>3</sub><sup>-1</sup> through the same procedure. In addition, a blank test using H<sub>2</sub>SO<sub>4</sub>, employing 0.1 M HCl both with and without N<sub>2</sub>H<sub>4</sub>-H<sub>2</sub>SO<sub>4</sub>, was performed to ascertain the presence of NO<sub>3</sub><sup>-1</sup> in the acid in significant quantities. The presence of traces of organic matter in the H<sub>2</sub>SO<sub>4</sub> substantially increased its ultraviolet absorption, necessitating the elimination of these traces by boiling the acid prior to use.

## Results

### *Agronomic traits of maize*

Application of urea fertilizer (UF) and slow-release nitrogen fertilizer (SRNF) exhibited significant difference ( $P \leq 0.05$ ) for plant height, biological yield, grain yield and stalk yield in Figure 1. Results regarding plant height, tallest plant height was achieved by 70% application of slow release that was statistically at par with 70% UF and 85% SRNF whereas the shortest plant height was taken in 100% UF application treatment. As far as biological yield and grain yield the maximum biological and grain yield was recorded in 70% SRNF that was statistically similar with 85% SRNF and the minimum was gathered by 100% Urea fertilizer application treatment. For stalk yield, the highest stalk yield was measured in 70% SRNF application treatment that was statistical at par with 70% urea fertilizer application and 80% slow-release nitrogenous fertilizer whereas the lowest stalk yield was recorded in 100% urea fertilizer application treatment (Figure 1).

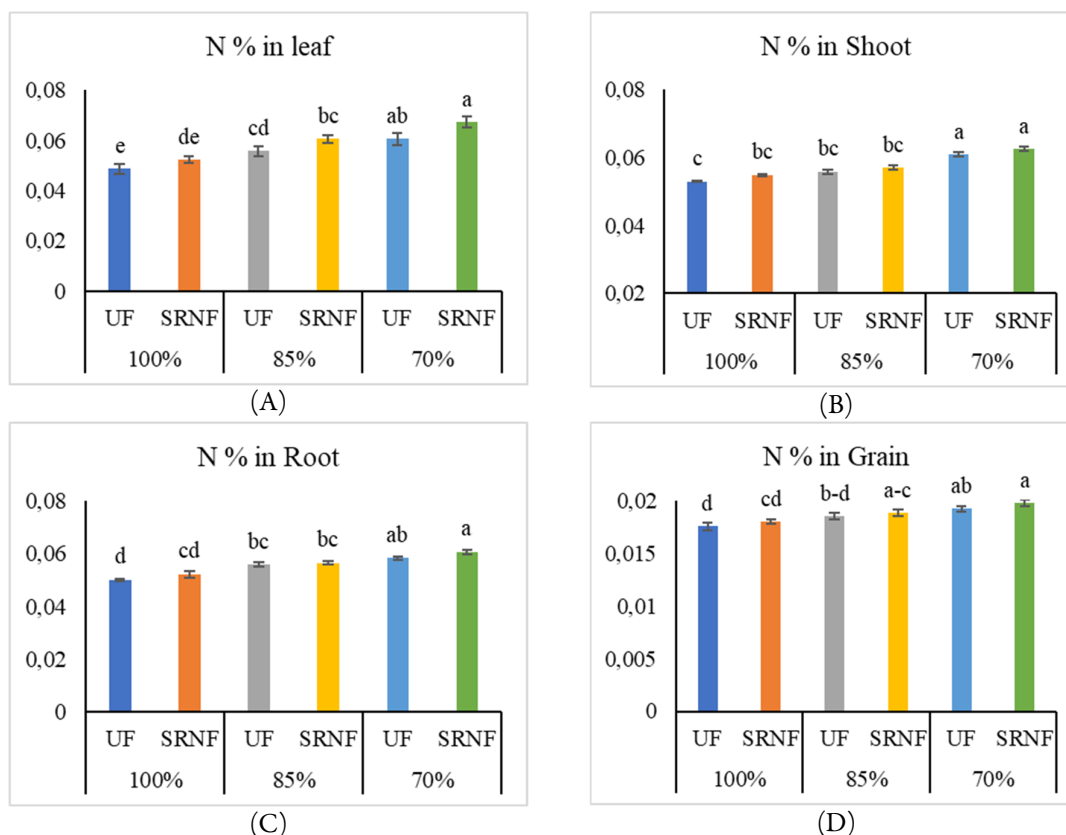


**Figure 1.** Effects of urea fertilization (UF) and slow-release nitrogen fertilizer (SRNF) treatments on Plant height (cm), biological yield, grain yield and stalk yield of maize. Different letters indicate significant differences at a level of significance of  $p \leq 0.05$ .

### *Nitrogen concentration*

Figure 2 revealed that the nitrogen concentrations in leaf, root, shoot and grains were significantly affected by different levels of urea fertilizer (UF) and slow-release nitrogen fertilizer (SRNF). For nitrogen percentage the maximum nitrogen concentration (0.07%) was achieved in which SRNF-70% was applied whereas the minimum was recorded in SRNF-100% (0.03%) was applied respectively. Plots treated with SRNF; nitrogen concentration was found statistically at par with plots treated with conventional urea. Urea fertilizer treated plots showed poor nitrogen contents and it significantly decreased by lowering urea doses.

Urea fertilizer 100% (0.01%) and nitrogen concentration (0.02%) in treatment where Urea fertilizer-70% was applied which was the lowest value.



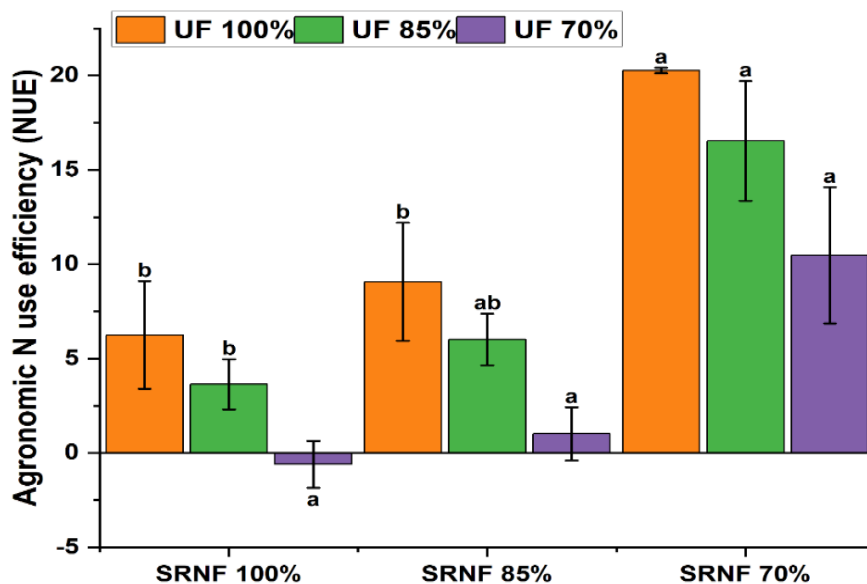
**Figure 2.** Impact of slow-release nitrogen fertilizer (SRNF) and urea fertilizers (UF) on (A) Nitrogen concentration in leaf of maize, (B) = Nitrogen concentration in shoot of maize, (C) = Nitrogen concentration in roots of maize, (D) = Nitrogen concentration in grains of maize, (E) = Plant height of maize (cm)

Different letters indicate significant differences at a level of significance of  $p \leq 0.05\%$ .

It was observed by analysis of variance and HSK ( $P \leq 0.05$ ) test that nitrogen percentage in root was maximum after application of product 70%. The nitrogen percentage after product application 100% was significantly different from both urea fertilizer 100% and slow-release nitrogen fertilizer 70%. Hence minimum amount of nitrogen was observed after urea fertilizer (UF) application 100%. These results clarified that application of slow-release nitrogen fertilizer (SRNF) significantly enhanced maize N concentration, and its 70% application was most effective. 0.34% N was observed as maximum after 70% product application and least value for N concentration in percentage 0.24% after applying urea fertilizer 100%. Product application enhanced 10% N as compared to urea fertilizer application. These results suggested that slow-release nitrogen fertilizer (SRNF) was most effective as compared to urea for N concentration in maize root. It was statistically observed that nitrogen percentage in maize shoot increased with application of slow-release nitrogen fertilizer in comparison with urea fertilizer (Figure 2).

For nitrogen content in shoot, it was revealed that there had been significant differences in N percentage in maize shoot under different treatments. The highest percentage of N concentration in shoot was observed after application of slow-release nitrogen fertilizer 70%. The lowest N percentage in shoot was observed after urea-fertilizer 100% application. The highest value of N percentage was 0.7% and lowest was 0.4% observed after slow-release nitrogen fertilizer 70% and urea 100% application respectively (Figure 2). Figure 3 revealed

that the nitrogen use efficiency (NUE) was significantly affected by different levels of urea fertilizer and slow-release nitrogen fertilizer (SRNF). Maximum NUE was observed in SRNF plots. The nitrogen use efficiency (NUE) for SRNF 100% dose was 33%, more significant than that of urea fertilizer 100% (17%) (Figure 3).



**Figure 3.** Impact of slow-release N fertilizer (SRNF) and urea fertilizer (UF) on agronomic nitrogen use efficiency of maize

Different letters indicate significant differences at a level of significance of  $p \leq 0.05\%$ .

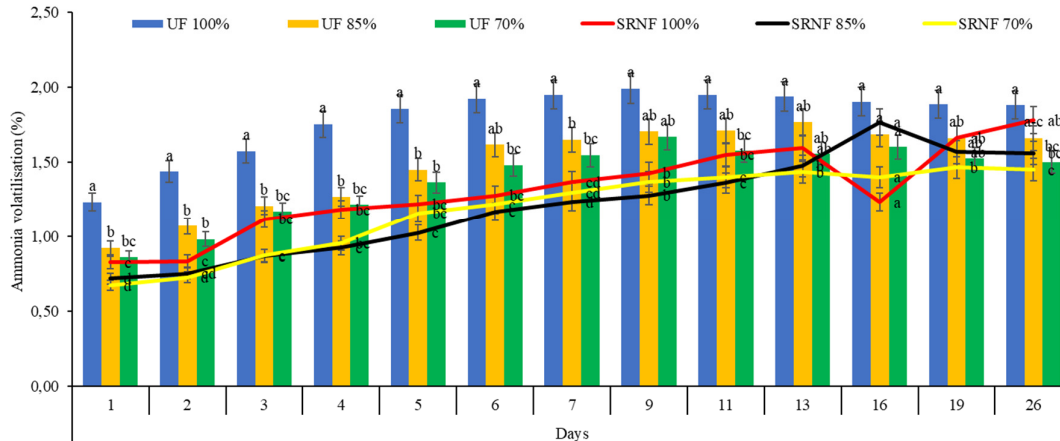
#### *Laboratory experiment*

#### Ammonia volatilization from urea fertilizer (UF) and slow-release nitrogen fertilizer (SRNF) under maize

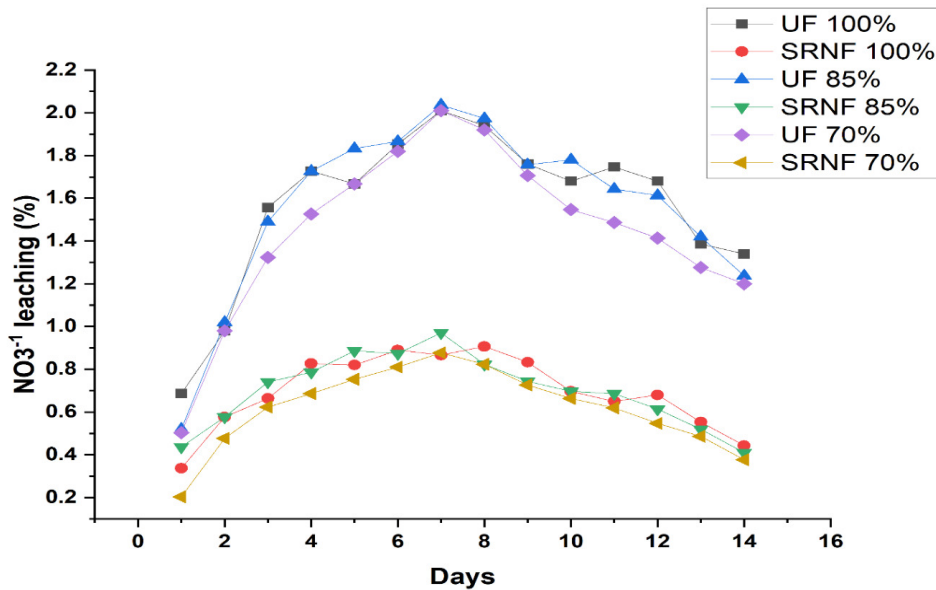
Ammonia volatilization increased steadily in the urea treated soil during the early incubation period until about 9 days after which no further  $\text{NH}_3$  emission took place. Interaction of different coating thicknesses of urea fertilizer and slow-release nitrogen fertilizer and days were statistically analyzed and found significant effect. Urea fertilizer was found less efficient in slowing down nitrogen release as maximum nitrogen contents were released within first 1 to 9 days ( $1.8 \text{ mg g}^{-1}$  of soil), compared to different number of coatings of SRNF ( $1.68 \text{ mg g}^{-1}$ ). While the nitrogen release from SRNF was slow and consistent because coatings of polymer hold the nutrient and slowed down rate of its release. Among days, maximum nitrogen release was observed in SRNF after 11 days interval as this coating thickness was comparatively less firm than other number of coating layers on SRNF fertilizer. After 13 to 16 days of incubation, SRNF showed almost constant nitrogen release from one time interval to another up to a certain limit except urea fertilizer. Maximum nitrogen content was observed in 70% SRNF. 85% SR slow releasing nitrogen fertilizer also showed a significant increase in nitrogen content compared to previous determination, but release was slow compared to 70% slow releasing nitrogen fertilizer. After 16 days of incubation period there was increased nitrogen concentration in soil treated with SRNF followed by urea fertilizer. From slow releasing nitrogen fertilizer the nitrogen release was decreased. After 19 and 26 days of incubation 70% slow-release nitrogen fertilizer showed least nitrogen release among the urea fertilizer treatments, but it was still significantly higher than other treatment fertilizer. In case of 85% slow-release nitrogen fertilizer concentration in soil was also significantly higher from the 100% treatment incubation period. Moreover, nitrogen concentration in soil was also more than that of 100% urea fertilizer and slow-release nitrogen fertilizer, because of the presence of urea fertilizer (Figure 4).

Urea fertilizer (UF) and slow-release nitrogen fertilizer (SRNF) on NO<sub>3</sub>-N leaching

Urea fertilizer was applied, nitrate (NO<sub>3</sub><sup>-</sup>) leaching occurred at a greater rate. Leaching increased from day 1 to day 6 continuously and afterward it decreased. In urea fertilizer leaching occurred at the rate of 2.13 mg L<sup>-1</sup>. Whereas in slow-release nitrogen fertilizer (SRNF), leaching occurred at the rate of 0.88 mg L<sup>-1</sup> which shows that SRNF is effective in controlling NO<sub>3</sub><sup>-</sup> losses (Figure 5).



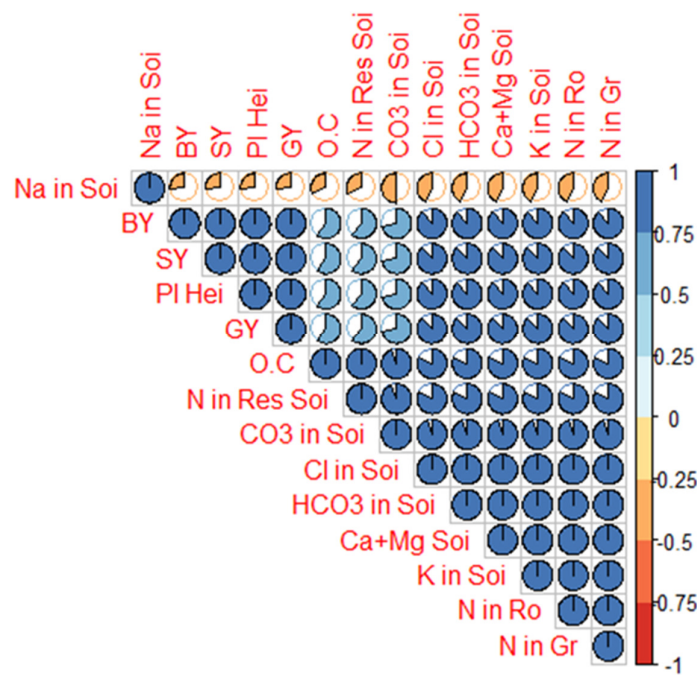
**Figure 4.** Ammonia volatilization under ordinary urea vs. slow-release nitrogen fertilizers (SNFR) Error bars indicate standard deviation of means (n=3). 100% recommended urea show high volatilization as compared to the urea 100% SRNF this shows that NH<sub>3</sub> volatilization is higher in 100% urea fertilizer as compared to slow-released nitrogen fertilizer; while the 85% recommended urea show moderate losses and the 70% recommended urea fertilizer and SRNF show the less NH<sub>3</sub> volatilization under maize crop. Tukey’s test was used to test the effect of different treatments, and the least significant difference (LSD) was calculated to compare the differences between means in each treatment. Values are the means ± SD of three replicates. The values followed by the different letters show statistically significant differences at P≤0.05.



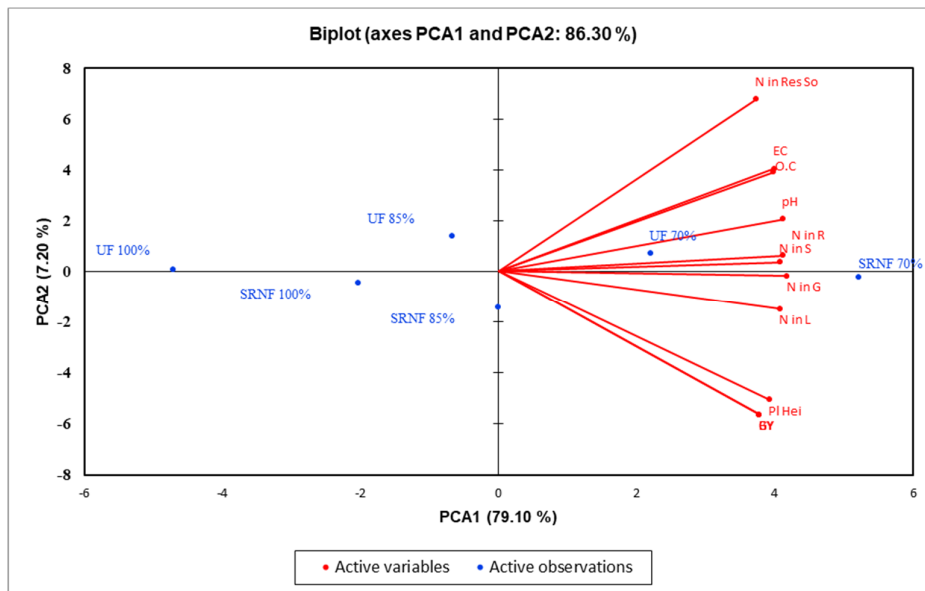
**Figure 5.** NO<sub>3</sub><sup>-</sup> leaching under ordinary urea fertilizer (UF) vs. slow-release nitrogen fertilizers (SNFR) Error bars indicate standard deviation of means (n=3). 100% recommended urea show high volatilization as compared to the urea fertilizer (UF) 100% SRNF this shows that NH<sub>3</sub> volatilization is higher in 100% urea fertilizer (UF) as compared to slow-released nitrogen fertilizer (SRNF); while the 85% recommended urea show moderate losses and the 70% recommended urea fertilizer (UF) and SRNF show the less NH<sub>3</sub> volatilization under maize crop.

*Results from Pearson correlation and principal component analysis*

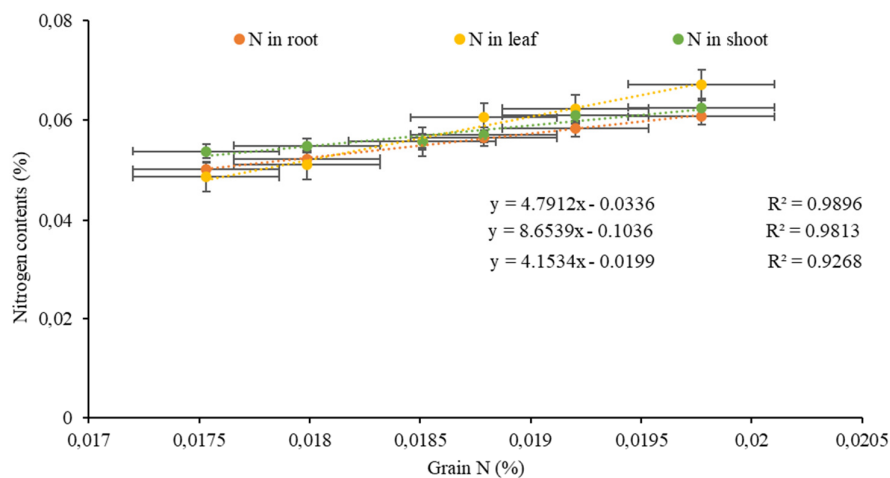
Significant positive and negative correlations were observed among plant growth (plant height, shoot dry weight, root dry weight, and grains weight) and physiological (internal carbon dioxide concentration, and SPAD index) parameters along with N, P and K contents of maize in soil and plant tissues in plots treated with slow-release nitrogen fertilizer (SRNF) (Figure 6). The score and loading plots of a principal component analysis (PCA) are presented in Figure 7. Within the dataset, the first two components of PCA revealed maximum 86.21% (A) and 73.43% (B) variations among all the studied parameters, of which PC1 explained a 8.59% (A) and 87.87% (B) variation whereas PC2 explained 3.62% (A) and 10.55% (B) variation. Moreover, all of the applied treatments were successfully displaced with the first two components. This displacement of treatments provided a clear indication that the application of coated urea slow-release nitrogen fertilizer and urea fertilizer along with MOP had a significant ameliorative effect on all the studied attributes of maize plants relative to the control. Here, PC1 was positively influenced by variables PCA having parameters photosynthesis rate, P and K in root, N in shoot, N in root, dry biological yield, dry straw yield, leaf area, dry cob yield, grain yield, cob diameter, cob length, plant height and SPAD), whereas PC2 was positively influenced by observations PCA containing (slow-release nitrogen fertilizer). The relationship between N volatilization and N use efficiency for various slow-release nitrogen fertilizer combination. However, it is depicted that the maximum N use efficiency and minimum N volatilization were seen with slow-release nitrogen fertilizer (SRNF) (Figure 8).



**Figure 6.** Pearson correlation for agronomic, physiological and biochemical characteristics of maize, as well as maize grain nitrogen contents under the influence of applied slow-release nitrogen fertilizer fertilizers (SRNF), have a significant connection ( $p = 0.05$ ).



**Figure 7.** The first two components revealed 79.10% (A) and 86.30% of the variability between the applied treatments and examined the parameters of maize plants under slow-release nitrogen fertilizer (SRNF) and urea fertilizers (UF) in a principal component analysis of observations and variables. Observations are UF 100%, UF 85%, UF 70% and SRNF 100%, SRNF 85%, SRNF 70



**Figure 8.** Relationship between Nitrogen volatilization and Nitrogen use efficiency (NUE) for value-added and conventional N fertilizers

## Discussion

The loss of nitrogen in the form of ammonia ( $\text{NH}_3$ ) volatilization from applied fertilizers is typically estimated to range between 20% and 30%. This loss can become more pronounced as soil pH and temperature increase, as observed in the study by Wolf *et al.* (1982).  $\text{NH}_3$  volatilization results in the creation of reactive nitrogen compounds, which are known to contribute to environmental pollution. When  $\text{NH}_3$  volatilization occurs, urea-based fertilizers lose a significant amount of nitrogen (N), leading to both environmental pollution and reduced crop yields and nutrient utilization efficiency. In response to the challenge of minimizing nitrogen

losses and improving the effectiveness of fertilizer use, various strategies have been implemented in the past. One of the notably successful approaches, as discussed by Gagnon *et al.* (2010) and further supported by Gagnon *et al.* (2018), involves enhancing conventional nitrogen fertilizers. This method entails integrating micronutrients and beneficial microorganisms into the fertilizers, which can enhance crop performance by interacting with essential nutrients and improving soil health. Research has demonstrated that the use of polymer-coated nitrogen fertilizers can effectively reduce ammonia losses and leaching during specific periods. For instance, the application of coated fertilizers, known as slow-release nitrogen fertilizers (SRNF), has been shown to substantially decrease  $\text{NH}_3$  emissions when compared to the traditional urea fertilizer (UF) application approach in crops. This reduction can be attributed to reduced exposure of ammoniacal nitrogen to the atmosphere, which minimizes further reactions, as observed in Barker *et al.* (2016) study. However, it's worth noting that ammonia emissions from urea fertilizer tend to be relatively higher than those from slow-release nitrogen fertilizers, possibly due to inadequate coating on SRNF granules, leading to quick rupture, especially in standing water conditions in crops like maize. Moreover, when agricultural plants efficiently utilize the supplied fertilizer, the risk of undesirable outcomes is significantly reduced. This maximum utilization of nitrogen can result in minimal ammonia emissions, as evidenced in our study, where polymer-coated nitrogen fertilizer exhibited greater recovery and use efficiency compared to other value-added fertilizers, a finding supported by research from Junejo *et al.* (2011) and Bryant-Schlobohm *et al.* (2020). It's important to note that once applied, nitrogen fertilizer undergoes a series of transformations, including conversion to ammonium, which is taken up by plants, nitrification into nitrate, fixation in soil colloids, leaching, and potential volatilization as ammonia. Compared to the standard surface application of uncoated nitrogen (N) fertilizer, polymer-coated fertilizers demonstrated significantly enhanced plant growth parameters in maize crops, as illustrated in Table 2. The improved performance is largely attributed to the enhanced availability of nitrogen, which, when optimal, supports increased carbohydrate production. These carbohydrates contribute to the development of the upper portions of the plants when nitrogen is readily accessible to them over an extended period. Consequently, the utilization of coated nitrogen fertilizers can be credited as the primary reason for the sustained availability of nitrogen to crop plants, resulting in heightened growth performance.

A higher number of tillers and greater wheat yields were documented when utilizing slow-release nitrogen fertilizers (Ghafoor *et al.*, 2021). The favorable results achieved with various slow-release nitrogen fertilizers, particularly when administered in varying quantities, can be ascribed to their capacity to reduce the release of nutrients into the atmosphere. Furthermore, research has suggested that deep placement of nitrogen fertilizers is linked to augmented plant growth and increased biomass. Notably, when compared to urea fertilizer, treatments with slow-release nitrogen fertilizers (SRNF) led to elevated chlorophyll levels in maize leaves at the point of physiological maturity. (Figures 2 and 3). A steady supply of N is required for the improved chlorophyll molecules, because N is a structural component of the molecule. According to the results of this study, the synthesis of chlorophyll in maize may have been affected by the slow release of N by recommended N fertilizers. The chlorophyll contents of wheat and fine rice were increased by using coated N fertilizers and the deep placement of N fertilizer (Oad *et al.*, 2004; Khalofah *et al.*, 2021). Slow releasing nitrogen fertilizer outperformed standard urea fertilizer (UF) in increasing maize yields across the board, including grain yield, straw yield, and biological output (Table 3). Zinc as a micronutrient have interaction with other plant nutrients like N and P. Slow-release nitrogen fertilizer have an additive effect for iron coating that may have synergistic interactions with other nutrients, especially N and P, that accounted for better crop yields. Nitrogen contributes directly to increased crop yields, but its synergistic interactions with other nutrients magnify its impact Li *et al.* (2021). Slow releasing nitrogen fertilizer was found to increase crop yields in this study, probably due to the minimal damage that N fertilizer grain can do to seedlings, as described by Yaseen *et al.* (2021) and Azeem *et al.* (2014), as toxic levels of a vital nutrient near the seedling's roots might damage its growth, resulting in a lower crop yield. Increased nutrient concentrations in soil can stunt plant growth if roots are exposed to it directly without the covering layer protecting them. Therefore, it is possible that coated N fertilizer is

responsible for the increased production. Coated N fertilizers were found to greatly increase maize yields when compared to uncoated N fertilizers Dong *et al.* (2016). When coated fertilizers were used, the plant's ability to absorb nutrients was improved, so N, P, and K concentrations were higher in different plant sections of maize in coated treatments than in uncoated ones (Figures 5-7). Nitrogen uptake is directly influenced by the application of recommended N fertilizers, as demonstrated in this study. Uncoated urea fertilizer (UF) showed the lowest concentration of N in all plant sections examined, whereas coated urea showed a higher concentration. This could be due to increased N availability in the root zone soil, as well as low N losses to the environment. An increase in N fertilizer uptake by field crops was reported by Folina *et al.* (2021). Deep N fertilizer placement also increased rice crop N uptake Rea *et al.* (2019). Another intriguing finding was the influence of different urea fertilizer value application on the concentrations of P and K in plant parts, with the maximum concentrations in plant parts being seen with polymer-coated fertilizers followed by slow-release fertilizer NPK and urea fertilizer treatment (Table 3). This may be due to the effect of the interactive effect of nutrients in the soil, which alters the soil microenvironment. A cationic form of N known as ammonium can be used by plants to mobilize P from organic sources and fixed P complexes. Hachiya *et al.* (2017). Because of the exchange mechanism that occurs when plants take in cationic form, the soil rhizosphere becomes acidic. In addition, urea to ammonium conversion results in acidic soil conditions. Burton *et al.* (2001). Consequently, the plant parts may have a larger concentration of P due to the solubilization of the fixed P in the soil. Because of urea fertilizer and ammonium nitrate fertilizer, soil pH has fallen Tian *et al.* (2015). Similarly, a decrease in soil pH has a significant effect on plant nutrition (Neina *et al.*, 2019). Increasing the concentration of K in plant parts may be a result of this interaction between N and K, as N plays a function in the acquisition of K in higher plants Fageria *et al.* (2014) and Milford *et al.* (2009) found that N and K interact synergistically in rice, wheat and other field crops.

Slow-release nitrogen fertilizer (SRNF) have shown the highest agronomic and recovery N usage efficiency in this study (Figures 7 and 8), which may be related to the minimal N losses and maximal consumption of N released from fertilizer granule. Increased crop N absorption is a result of increased soil N availability, which has a direct impact on plant physiological and metabolic processes. An increase in yield can be achieved by cultivating plants that have more metabolic and physiological activity. When more N is ingested, the efficiency of reusing N is increased Wu *et al.* (2017). Slow-release N fertilizer enhanced sunflower N utilization efficiency in a study. Perveen *et al.* (2021). The activation of indigenous P and K solubilizing bacteria in the soil may have influenced the efficiency of P and K consumption in the study, as urea fertilizer NPK contains plant growth promoting rhizobacterial strain in the coating material that boosts microbial activity in the soil. P and K fixation with counter ions and clay colloids can be minimized by microbial activities in the soil. Slow releasing nitrogen fertilizer might be due to the iron coating performed better than standard urea fertilizer in improving N use efficiency. In a similar study, Imran *et al.* (2018) proved that the simultaneous application of plant nutrients resulted in higher nutrient use efficiencies. In the experiments, slow releasing nitrogen fertilizer outperformed urea fertilizer (UF) sources in terms of performance. Moreover, water and counter ions react with the covering substance, preventing the internal contents from being exposed to these ions or water molecules. Therefore, it is possible that coated fertilizers enhanced growth, yield and nutrient use efficiency with lower ammonia emissions due to the coating layer's ability to protect nutrients. Using slow-release nitrogen fertilizer (SRNF) wheat and other field crops were able to use their N more efficiently because of the slower release of N. Folina *et al.* (2021) Hegab *et al.* (2018). It was found that SRNF with standard urea fertilizer (UF) in terms of plant growth, yield and nutrient usage efficiency. This might be due to the better lower nutrient exposure to the atmosphere, as both these fertilizers were coated. A reduction in N gaseous loss and an increase in maize biomass and yield were both achieved by applying N fertilizer deeply. Adjetey *et al.* (1999) and Can *et al.* (2021) However, SRNF fertilizers performed better in comparison to the standard UF sources, while SRNF ideally improved growth, yield, and nutrient utilization efficiency with a considerable decrease in ammonia volatilization. As a result of the current approach, farmers' income and food quality can

be improved, and the environment can be protected from dangerous gas emissions like ammonia from the use of N fertilizers. Borchard *et al.* (2019) used slow-release nitrogen fertilizer for reducing  $\text{NO}_3^-$  leaching and  $\text{N}_2\text{O}$  emissions. The overall  $\text{N}_2\text{O}$  emissions reduction was 38%, while  $\text{NO}_3^-$  leaching was reduced by 13% with slow-release nitrogen fertilizer application. Slow-release nitrogen fertilizer had the strongest  $\text{N}_2\text{O}$  emission reducing effect in paddy soils (Anthrosols) and sandy soils (Arenosols). The use of slow-release nitrogen fertilizer reduced both  $\text{N}_2\text{O}$  emissions and  $\text{NO}_3^-$  leaching in arable farming and horticulture. Sika *et al.* (2014) showed that slow-release nitrogen fertilizer has the potential in reducing inorganic N leaching losses from inorganic and organic fertilizer sources in coarse-textured soils. Laboratory columns containing sandy soil and slow-release nitrogen fertilizer (0, 0.5, 2.5 and 10.0% w/w) were leached weekly over a period of six weeks simulating heavy winter rainfall. Slow-release nitrogen fertilizer (0.5, 2.5 and 10.0% w/w) significantly reduced the cumulative amount of ammonium ( $\text{NH}_4^+$ ) (12, 50 and 86%, respectively) and  $\text{NO}_3^-$  (26, 42 and 96%, respectively) leached relative to the control soil. Despite the strong reduction in inorganic N leaching was observed, the leached slow-release nitrogen fertilizer amended soils contained only small amounts of exchangeable  $\text{NH}_4^+$  (0-7.3  $\text{mg kg}^{-1}$ ) and  $\text{NO}_3^-$  (5.8-8.0  $\text{mg kg}^{-1}$ ). The results showed that slow-release nitrogen fertilizer can strongly reduce not only the amount of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  leached from sandy soils, but also the amount of recoverable exchangeable  $\text{NH}_4^+$  and  $\text{NO}_3^-$  after leaching.

## Conclusions

Slow-release nitrogen fertilizer (SRNF) has a strong impact on the growth and yield of maize crops; these fertilizers improve the nutrition of crops very effectively. We found that polymer-coated N fertilizers were more efficient in reducing volatilization losses in comparison to the commercially available sources like urea fertilizer (UF). Moreover, Slow-release nitrogen fertilizer (SRNF) was very effective in improving fertilizer use efficiency in addition to the reduction in N losses. We thus concluded that the utilization of slow-release (polymer-coated) fertilizers in maize extensive cropping systems not only improves crop production via increased nutrient use efficiencies but is also environmentally friendly, owing to their biodegradability and reduced ammonia and volatilization losses. Additional studies are required to compare the efficacy of coated fertilizers with those of commercially available fertilizers to perform a precise cost benefit evaluation on long-term field trials.

## Authors' Contributions

Conceptualization: FF; Writing - original draft: HR; Methodology: MA; Investigation: AA; Data curation: MDM, AUR, JI; Formal analysis SAA, MJA; Project administration: AQ; Resources: MJA; Software: MA and AQ; Supervision: MA; Validation: JI; Visualization: AUR; Writing - review and editing: MA, AQ. All authors read and approved the final manuscript.

## Ethical approval (for researches involving animals or humans)

Not applicable.

## Acknowledgements

This project was supported by Researchers Supporting Project number (RSP2025R5), King Saud University, Riyadh, Saudi Arabia.

## Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

## References

- Abbasi MR, Sepaskhah AR (2023). Nitrogen leaching and groundwater n contamination risk in saffron/wheat intercropping under different irrigation and soil fertilizers regimes. *Scientific Reports* 13:6587. <https://doi.org/10.1038/s41598-023-33817-5>
- Adjetej JA, Campbell LC, Searle PGE, Saffigna P (1999). Studies on depth of placement of urea on nitrogen recovery in wheat grown on a red-brown earth in Australia. *Nutrient Cycling in Agroecosystems* 54:227-232. <https://doi.org/10.1023/A:1009775622609>
- Baker ET, Resing JA, Haymon RM, Tunnicliffe V, Lavelle JW, Martinez F, Ferrini V, Walker SL, Nakamura K (2016). How many vent fields? New estimates of vent field populations on ocean ridges from precise mapping of hydrothermal discharge locations. *Earth and Planetary Science Letters* 449:186-96. <https://doi.org/10.1016/j.epsl.2016.05.031>
- Barber SA (1976). Efficient fertilizer use. In: Patteron FL (Ed). *Agronomic research for food*. Special Publication 26. American Society of Agronomy, Madison, Wisconsin, USA.
- Bisht N, Chauhan PS (2020). Excessive and disproportionate use of chemicals cause soil contamination and nutritional stress. *Soil Contamination-Threats and Sustainable Solutions* 1-10.
- Borchard N, Schirrmann M, Cayuela ML, Kammann C, Wrage-Mönnig N, Estavillo JM, ... Novak J (2019). Biochar, soil and land-use interactions that reduce nitrate leaching and N<sub>2</sub>O emissions: a meta-analysis. *Science of the Total Environment* 651:2354-64. <https://doi.org/10.1016/j.scitotenv.2018.10.060>
- Bryant-Schlobohm R, Dhillon J, Wehmeyer GB, Raun WR (2020). Wheat grain yield and nitrogen uptake as influenced by fertilizer placement depth. *Agrosystems, Geosciences & Environment* 3(1):e20025. <https://doi.org/10.1002/agg2.20025>
- Burton SA, Prosser JI (2001). Autotrophic ammonia oxidation at low pH through urea hydrolysis. *Applied and Environmental Microbiology* 67:2952-2957. <https://doi.org/10.1128/AEM.67.7.2952-2957.2001>
- Can ZH, Huang H, Qian ZH, Jiang HX, Liu GM, Ke XU, Hu YJ, Dai QG, Huo ZY (2021). Effect of side deep placement of nitrogen on yield and nitrogen use efficiency of single season late japonica rice. *Journal of Integrative Agriculture* 20:1487-1502. [https://doi.org/10.1016/S2095-3119\(20\)63362-7](https://doi.org/10.1016/S2095-3119(20)63362-7)
- Dong YJ, He MR, Wang ZL, Chen WF, Hou J, Qiu XK, Zhang JW (2016). Effects of new coated release fertilizer on the growth of maize. *Journal of Soil Science and Plant Nutrition* 16:637-649. <http://dx.doi.org/10.4067/S0718-95162016005000046>
- Duan J, Ren C, Wang S, Zhang X, Reis S, Xu J, Gu B (2021). Consolidation of agricultural land can contribute to agricultural sustainability in China. *Nature Food* 2:1014-1022. <https://doi.org/10.1038/s43016-021-00415-5>
- Fageria NK, Oliveira JP (2014). Nitrogen, phosphorus and potassium interactions in upland rice. *Journal of Plant Nutrition* 37:1586-1600. <https://doi.org/10.1080/01904167.2014.920362>
- Folina A, Tataridas A, Mavroeidis A, Kousta A, Katsenios N, Efthimiadou A, ... Kakabouki I (2021). Evaluation of various nitrogen indices in N-fertilizers with inhibitors in field crops: A review. *Agronomy* 11:418. <https://doi.org/10.3390/agronomy11030418>
- Gagnon B, Ziadi N (2010). Grain corn and soil nitrogen responses to sidedress nitrogen sources and applications. *Agronomy Journal* 102:1014-22. <https://doi.org/10.2134/agronj2010.0011>

- Gagnon B, Ziadi N, Rochette P, Chantigny MH, Angers DA, Bertrand N, Smith WN (2016). Soil-surface carbon dioxide emission following nitrogen fertilization in corn. *Canadian Journal of Soil Science* 96:219-32. <https://doi.org/10.1139/cjss-2015-0053>
- Ghafoor I, Habib-ur-Rahman M, Ali M, Afzal M, Ahmed W, Gaiser T, Ghaffar A (2021). Slow-release nitrogen fertilizers enhance growth, yield, NUE in wheat crop and reduce nitrogen losses under an arid environment. *Environmental Science and Pollution Research* 28:43528-43543. <https://doi.org/10.1007/s11356-021-13700-4>
- Government of Pakistan (2023). Economic Survey of Pakistan. Economic Advisory Wing, Finance Division, Islamabad.
- Hachiya T, Sakakibara H (2017). Interactions between nitrate and ammonium in their uptake, allocation, assimilation, and signaling in plants. *Journal of Experimental Botany* 68:2501-2512. <https://doi.org/10.1093/jxb/erw449>
- Hegab RH (2018). Evaluation of nitrogen sources and polymer coated fertilizers on wheat yield in sandy soil. *Asian Journal of Soil Science and Plant Nutrition* 3:1-12. <https://doi.org/10.9734/AJSSPN/2018/44164>
- Heidari AA, Mahdavi H, Kahriz PK (2022). TFC solvent-resistant nanofiltration membrane prepared via a gyroid-like PE support coated with polydopamine/Tannic acid-Fe (III). *Journal of Industrial and Engineering Chemistry* 106:400-410. <https://doi.org/10.1016/j.jiec.2021.11.017>
- Huang J, Gómez-Dans JL, Huang H, Ma H, Wu Q, Lewis PE, ... Zhao F (2019). Assimilation of remote sensing into crop growth models: Current status and perspectives. *Agricultural and Forest Meteorology* 276:107609. <https://doi.org/10.1016/j.agrformet.2019.06.008>
- Huang J, Ma H, Sedano F, Lewis P, Liang S, Wu Q, Su W, Zhang X, Zhu D (2019). Evaluation of regional estimates of winter wheat yield by assimilating three remotely sensed reflectance datasets into the coupled WOFOST-PROSAIL model. *European Journal of Agronomy* 102:1-3. <https://doi.org/10.1016/j.eja.2018.10.008>
- Imran M, Irfan M, Yaseen M, Rasheed N (2018). Application of glycerin and polymer coated diammonium phosphate in alkaline calcareous soil for improving wheat growth, grain yield and phosphorus use efficiency. *Journal of Crop Science and Biotechnology* 21:425-434. <https://doi.org/10.1007/s12892-018-0126-0>
- Javed T, Singhal RK, Shabbir R, Shah AN, Kumar P, Jinger D, ... Anuragi H (2022). Recent advances in agronomic and physio-molecular approaches for improving nitrogen use efficiency in crop plants. *Frontiers in Plant Science* 13:917. <https://doi.org/10.3389/fpls.2022.877544>
- Jeon M, Lee E, Kim M, Jegal H, Park S, Chi JH, Baek S, Lee J, Keel SI (2023). Nitric oxide (NO) and nitrous oxide (N<sub>2</sub>O) emissions during selective non-catalytic reduction and selective catalytic reduction processes in a pulverized coal/Ammonia Co-fired boiler. *Journal of Environmental Chemical Engineering*. 11:109398. <https://doi.org/10.1016/j.jece.2023.109398>
- Jiang Z, Yang S, Chen X, Pang Q, Xu Y, Qi S, Yu W, Dai H (2022). Controlled release urea improves rice production and reduces environmental pollution: A research based on meta-analysis and machine learning. *Environmental Science and Pollution Research* 29:3587-3599. <https://doi.org/10.1007/s11356-021-15956-2>
- Karatzak E, Dichala O, Papanastasi K, Manthos I, Ganopoulos I, Karydas A, ... Nikisianis N (2023). A multifaceted evaluation approach for Greek native neglected and underutilized forest fruit trees and shrubs as natural sources of antioxidants: Consolidating the framework for their sustainable agronomic exploitation. *Plants* 12:1642. <https://doi.org/10.3390/plants12081642>
- Khalofah A, Khan MI, Arif M, Hussain A, Ullah R, Irfan M, ... Brtnicky M (2021). Deep placement of nitrogen fertilizer improves yield, nitrogen use efficiency and economic returns of transplanted fine rice. *PLoS ONE* 16:e0247529. <https://doi.org/10.1371/journal.pone.0247529>
- Khan AA, Qadar G, Abro AA, Awais M (2023). Tomato yield losses due to attack of insects/pests in Pakkhal Valley of District Mansehra Khyber Pakhtunkhwa, Pakistan. *Sarhad Journal of Agriculture*. *Sarhad Journal of Agriculture* 39:21-28. <https://dx.doi.org/10.17582/journal.sja/2023/39.1.21.28>
- Li L, Tian H, Zhang M, Fan P, Ashraf U, Liu H, ... Zhang Z (2021). Deep placement of nitrogen fertilizer increases rice yield and nitrogen use efficiency with fewer greenhouse gas emissions in a mechanical direct-seeded cropping system. *The Crop Journal* 9:1386-1396. <https://doi.org/10.1016/j.cj.2020.12.011>
- Liu J, Wang Y, Li Y, Peñuelas J, Zhao Y, Sardans J, ... Li Y (2023). Soil ecological stoichiometry synchronously regulates stream nitrogen and phosphorus concentrations and ratios. *Catena* 231:107357. <https://doi.org/10.1016/j.catena.2023.107357>

- Mangani R, Tesfamariam EH, Engelbrecht CJ, Bellocchi G, Hassen A, Mangani T (2019). Potential impacts of extreme weather events in main maize (*Zea mays* L.) producing areas of South Africa under rainfed conditions. *Regional Environmental Change* 19:1441-1452. <https://doi.org/10.1007/s10113-019-01486-8>
- Milford GF, Johnston AE (2009). Potassium and nitrogen interactions in crop production. *Nawozy Nawozenie* 34:143-162.
- Neina D (2019). The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science* 5794869. <https://doi.org/10.1155/2019/5794869>
- Noort MW, Renzetti S, Linderhof V, du Rand GE, Marx-Pienaar NJ, de Kock HL, Magano N, Taylor JR (2022). Towards sustainable shifts to healthy diets and food security in sub-Saharan Africa with climate-resilient crops in bread-type products: A food system analysis. *Foods* 11:135. <https://doi.org/10.3390/foods11020135>
- Page AL, Miller RH, Keeney DR (1982). *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties.* American Society of Agronomy. In Soil Science Society of America, Madison, Wisconsin.
- Pajura R, Masłoń A, Czarnota J (2023). The use of waste to produce liquid fertilizers in terms of sustainable development and energy consumption in the fertilizer industry—A case study from Poland. *Energies* 16:1747. <https://doi.org/10.3390/en16041747>
- Perveen S, Ahmad S, Skalicky M, Hussain I, Habibur-Rahman M, Ghaffar A, ... Fahad S (2021). Assessing the potential of polymer coated urea and sulphur fertilization on growth, physiology, yield, oil contents and nitrogen use efficiency of sunflower crop under arid environment. *Agronomy* 11:269. <https://doi.org/10.3390/agronomy11020269>
- Powelson DS, Dawson CJ (2022). Use of ammonium sulphate as a sulphur fertilizer: Implications for ammonia volatilization. *Soil Use and Management* 38:622-634. <https://doi.org/10.1111/sum.12733>
- Puertas R, Marti L, Calafat C (2023). Agricultural and innovation policies aimed at mitigating climate change. *Environmental Science and Pollution Research* 30:47299-47310. <https://doi.org/10.1007/s11356-023-25663-9>
- Qiu H, Yang S, Jiang Z, Xu Y, Jiao X (2022). Effect of irrigation and fertilizer management on rice yield and nitrogen loss: A meta-analysis. *Plants* 11:1690. <https://doi.org/10.3390/plants11131690>
- Qiu S, Yang H, Zhang S, Huang S, Zhao S, Xu X, ... Nikolaidis N (2023). Carbon storage in an arable soil combining field measurements, aggregate turnover modeling and climate scenarios. *Catena* 220:106708. <https://doi.org/10.1016/j.catena.2022.106708>
- Rea RS, Islam MR, Rahman MM, Mix K (2019). Study of nitrogen use efficiency and yield of rice influenced by deep placement of nitrogen fertilizers. *SAARC Journal of Agriculture* 17:93-103.
- Ribeiro RH, Besen MR, Simon PL, Bayer C, Piva JT (2020). Enhanced-efficiency nitrogen fertilizers reduce winter losses of nitrous oxide, but not of ammonia, from no-till soil in a subtropical agroecosystem. *Soil Use and Management* 36:420-428. <https://doi.org/10.1111/sum.12575>
- Sahu BK, Nagargade M, Chandel M, Kaur K, Swami K, Kumar P, ... Shanmugam V (2022). Eco-friendly urea nanosack: Jute grafted silica nanoring woven fertilizer to control urea release and enhance crop productivity. *ACS Sustainable Chemistry & Engineering* 10:13357-13366. <https://doi.org/10.1021/acssuschemeng.2c03372>
- Schwartz SE, Benoit L, Clayton S, Parnes MF, Swenson L, Lowe SR (2023). Climate change anxiety and mental health: Environmental activism as buffer. *Current Psychology* 42:16708-16721. <https://doi.org/10.1007/s12144-022-02735-6>
- Sika MP, Hardie AG (2014). Effect of pine wood biochar on ammonium nitrate leaching and availability in a South African sandy soil. *European Journal of Soil Science* 65:113-9. <https://doi.org/10.1111/ejss.12082>
- Sinha D, Tandon PK (2020). An overview of nitrogen, phosphorus and potassium: Key players of nutrition process in plants. In: Mishra K, Tandon PK, Srivastava S (Eds). *Sustainable Solutions for Elemental Deficiency and Excess in Crop Plants.* Springer, Singapore. [https://doi.org/10.1007/978-981-15-8636-1\\_5](https://doi.org/10.1007/978-981-15-8636-1_5).
- Steel RG, Torrie JH, Dickey DA (1997). *Principles and procedures of statistics: a biometrical approach.* 3rd Edition, McGraw Hill, Inc. Book Co.
- Su F, Liu Y, Chen SJ, Fahad S (2023). Towards the impact of economic policy uncertainty on food security: Introducing a comprehensive heterogeneous framework for assessment. *Journal of Cleaner Production* 386:135792. <https://doi.org/10.1016/j.jclepro.2022.135792>

- Suman J, Rakshit A, Patra A, Dutta A, Tripathi VK, Mohapatra KK, Tiwari R, Krishnamoorthi S (2023). Enhanced efficiency N fertilizers: An effective strategy to improve use efficiency and ecological sustainability. *Journal of Soil Science and Plant Nutrition* 23:1472-1488. <https://doi.org/10.1007/s42729-023-01237-z>
- Tian D, Niu S (2015). A global analysis of soil acidification caused by nitrogen addition. *Environmental Research Letters* 10 024019. <https://doi.org/10.1088/1748-9326/10/2/024019>
- Tyagi J, Ahmad S, Malik M (2022). Nitrogenous fertilizers: Impact on environment sustainability, mitigation strategies, and challenges. *International Journal of Environmental Science and Technology* 19:11649-11672. <https://doi.org/10.1007/s13762-022-04027-9>
- Wolf B (1982). A comprehensive system of leaf analyses and its use for diagnosing crop nutrient status. *Communications in Soil Science and Plant Analysis* 13:1035-1059. <https://doi.org/10.1080/00103628209367332>
- Yaseen M, Ahmad A, Younas N, Naveed M, Ali MA, Shah SS, Hasnain M, Mustafa A (2023). Value-added fertilizers enhanced growth, yield and nutrient use efficiency through reduced ammonia volatilization losses under maize-rice cropping cultivation. *Sustainability* 15:2021 <https://doi.org/10.3390/su15032021>
- Yi J, Li H, Zhao Y, Zhang H, Liu M (2022). Assessing soil water balance to optimize irrigation schedules of flood-irrigated maize fields with different cultivation histories in the arid region. *Agricultural Water Management* 265:107543. <https://doi.org/10.1016/j.agwat.2022.107543>
- Zhang T, Li H, Yan T, Shaheen SM, Niu Y, Xie S, Zhang Y, Abdelrahman H, Ali EF, Bolan NS, Rinklebe J (2023). Organic matter stabilization and phosphorus activation during vegetable waste composting: Multivariate and multiscale investigation. *Science of The Total Environment* 891:164608. <https://doi.org/10.1016/j.scitotenv.2023.164608>
- Zhang T, Li P, Fang C, Jiang R (2014). Phosphate recovery from animal manure wastewater by struvite crystallization and CO degasification reactor. *Ecological Chemistry and Engineering S* 21:89-99. <https://doi.org/10.2478/eces-2014-0008>
- Zhang T, Song B, Han G, Zhao H, Hu Q, Zhao Y, Liu H (2023). Effects of coastal wetland reclamation on soil organic carbon, total nitrogen, and total phosphorus in China: a meta-analysis. *Land Degradation & Development* 34:3340-9. <https://doi.org/10.1002/ldr.4687>



The journal offers free, immediate, and unrestricted access to peer-reviewed research and scholarly work. Users are allowed to read, download, copy, distribute, print, search, or link to the full texts of the articles, or use them for any other lawful purpose, without asking prior permission from the publisher or the author.



**License** - Articles published in *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* are Open-Access, distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) License.

© Articles by the authors; Licensee UASVM and SHST, Cluj-Napoca, Romania. The journal allows the author(s) to hold the copyright/to retain publishing rights without restriction.

**Notes:**

- **Material disclaimer:** The authors are fully responsible for their work and they hold sole responsibility for the articles published in the journal.
- **Maps and affiliations:** The publisher stay neutral with regard to jurisdictional claims in published maps and institutional affiliations.
- **Responsibilities:** The editors, editorial board and publisher do not assume any responsibility for the article's contents and for the authors' views expressed in their contributions. The statements and opinions published represent the views of the authors or persons to whom they are credited. Publication of research information does not constitute a recommendation or endorsement of products involved.