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Managing reactive nitrogen in spring wheat cropping systems: insights from Kabul, Afghanistan

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Abstract

Ammonia (NH_3) volatilization and nitrate leaching are significant pathways of reactive nitrogen (N*r*) losses in agriculture, leading to environmental concerns. This study investigates nitrogen (N) losses in wheat production near Kabul, Afghanistan, aiming to improve nitrogen use efficiency (NUE) for food security and environmental protection. Three fertilizer treatments were tested: (A) animal manure (2 t h^{-1}) + 50% chemical fertilizer (urea and diammonium phosphate, DAP), (B) night soil (2 t ha^{-1}) + 50% chemical fertilizer, and (C) full dose of chemical fertilizer, with sub-treatments varying in N application (25% less, 25% excess, and farmers' practice). A no-fertilizer control treatment was included. Ammonia emissions and nitrate-N (NO_3-N) and ammonium (NH_4-N) leaching were monitored, and NUE was calculated. Subsurface application (treatment A_2) reduced ammonia emissions by 41.82% compared to 55% in surface applications (treatment A_3) and 15% in control plots. Ammonium-N losses were lower in subsurface application (31%) than surface applications (53%). NUE was highest in surface application (103%) and lowest in subsurface (84%). Moreover, Partial Factor Productivity (PFP) was higher in treatments with 25% less N compared to those with 25% excess and conventional practice. The novelty of this study lies in the implementation of subsurface application techniques to reduce N losses and enhance NUE in this region, where such techniques are rarely used. These results offer a model for improving NUE by optimizing fertilizer and manure inputs, applicable to similar agricultural systems globally.

1. Introduction

Nitrogen (N) constitutes a major component (78%) of the Earth's atmosphere in its gaseous form, making it inert and unreactive. It becomes reactive when converted into compounds such as ammonium (NH_4^+), ammonia (NH_3), nitrous oxide (N_2O), nitrate (NO_3^-), nitrite (NO_2^-), and nitrogen oxides (NO_x), leading to rapid turnover and potentially harmful environmental consequences. Growing concern over the escalating leakage of reactive nitrogen (N*r*) into the environment has underscored the need to understand its behavior and management, particularly as it has already exceeded the planetary boundary [1, 2].

In addition to the Haber–Bosch process, which converts gaseous N into N_r, several natural processes, such as biological N-fixation and lightning activity, also transform N_2 into N*r*. These processes are essential for food production and sustaining Earth's soil food webs. However, it is important to note that the effectiveness of these processes and management practices can vary by climate, crop type, and region. Striking a balance between meeting the demands of a growing population and the sustainable intensification of agriculture is crucial. Sustainable intensification aims to achieve higher crop yields while minimizing harmful environmental impacts, such as nitrate (NO_3^-) leaching [3]. The feasibility of the approach was demonstrated in a study by Mueller *et al* [4], which highlighted the significance of meticulous nutrient and water management for both food security and environmental sustainability.

The harmful effects of excess N*r* are numerous and far-reaching. Nitrogen losses from agricultural systems contribute to air pollution through ammonia (NH_3) emissions and to climate change via nitrous oxide (N_2O) emissions. Such emissions degrade air quality, contribute to the formation of particulate matter, and exacerbate acidification and eutrophication in ecosystems, further intensifying global warming. Ammonia (NH_3) is a significant air pollutant, contributing to both urban and rural air pollution. It accelerates the formation of fine particles in the atmosphere, leading to processes such as acidification and eutrophication in ecosystems, which, in turn, contributing to climate change [5, 6]. Particulate NH_3 also has detrimental effects on human health [7], including mutagenic and genotoxic activities through the generation of organic and inorganic aerosols that can adsorb toxic air pollutants [8]. Furthermore, excessive N*r* can lead to groundwater contamination, particularly through nitrate (NO_3^-) leaching, which poses significant health risks. In regions with intensive irrigation like Kabul, the risk of nitrate contamination of groundwater is a growing concern [9, 10]. The consequences of these Nr-related environmental issues include ecosystem degradation, reduced biodiversity, and increased health risks to humans.

Field experiments have shown that better management of water and N-fertilizer inputs can lead to higher crop yields and improved environmental performance, particularly in reducing gaseous emissions. A study by Grassini and Cassman [11] focused on irrigated maize in the USA, while research in China highlighted the benefits of improved rotations and fertilizer management in arable cropping [12]. These studies show that agronomic practices that optimize fertilizer use and irrigation can significantly reduce N losses. However, these practices may not be universally applicable, as they are climate- and crop-specific. Evaluating crop yield and environmental performance in terms of gaseous N emissions has been recognized as a valuable approach within the framework of sustainable intensification [13]. Jing *et al* [14] recommended the incorporation of manure as an essential strategy in N-fertilization management for upland red soil cropping systems, emphasizing diverse approaches to achieve sustainable and efficient nutrient management in agricultural practices.

The large-scale global production of N_r has played a critical role in meeting the growing food demands of the world's population [15]. However, agriculture is a major source of N*r* pollution, largely due to the inefficient use of fertilizers [16]. Excessive fertilizer use results in reactive nitrogen (N_r) losses, which have serious environmental consequences, including degradation of air quality and contributions to climate change. These issues emphasize the need for a thorough understanding of the pathways involved in order to develop effective management practices [14]. In addition to inefficient fertilizer use, factors such as soil N processing under specific environmental conditions and irrigation practices that promote higher nitrification/denitrification rates can contribute to higher N*r* losses.

Mismanagement of nitrogen sources (food, feed, and nutrients) in intensified agriculture can lead to increased levels of nitrite (NO_2^-), nitrate (NO_3^-), and ammonium (NH_4^+) in the soil, as well as elevated concentrations of ammonia (NH_3) and the greenhouse gas nitrous oxide (N_2O) in the atmosphere. Consequently, surpluses within the agricultural system [17] can escape into the environment, even in subtropical dry areas like Afghanistan, due to intensive irrigation practices. Leaching losses pose a high risk of groundwater contamination, with agriculture being a significant contributor to nitrate contamination of groundwater [18, 19].

In South Asia, the use of nitrogen fertilizers increased by 50% from 2002 and 2017, contributing to inefficient fertilizer use [20]. Reports by Bijay-Singh [21] indicate a decline in nutrient use efficiency (NUE) in India, with a reduction from 55% to 35% between 1960 and 2010. This decrease in NUE reflects a global trend driven by increased N-fertilization, resulting in less efficient utilization of N by crops [15]. The current NUE of our global food system has been estimated to be as low as 15% [22]. Excessive use of N_r can negatively affect ecosystems and human health, causing pollution of water, air, and soils, leading to ecosystem deterioration [23]. South Asia, in particular, is a global hotspot for N_r release [20]. In addition to inefficient fertilizer use, other factors such as soil N processing under specific environmental conditions, particularly in irrigated systems, could favor higher rates of nitrification/denitrification, contributing to increased N*r* losses.

The Kabul region faces significant challenges in managing nitrogen use efficiency and mitigating nitrogen losses. Intensive agricultural practices, combined with specific environmental conditions, exacerbate these issues. Irrigation plays a central role by enhancing nitrification and denitrification rates, leading to increased N losses. Excessive N fertilizer use, coupled with inefficient irrigation practices, has also led to serious groundwater contamination, particularly from nitrate leaching. These factors reduced NUE and contribute to sever health and ecological risks, such as water contamination, which pose direct threats to both the environment and public health.

Table 1. Overall physiognomies of the village and dominated farming system in Shewaki, Kabul, Afghanistan.

Socio-economics	Characteristics
Household orientation	Commercial and subsistence
Number of studied households	212
Agriculture and village area under study (km^2)	7.39[a]
Irrigation type	Flood and furrow
Main crops	Cereal and cash crops
Other crops grown	Potato, Summer squash, Tomato, Maize, Clover, Onion and etc
Fertilizers applied	DAP, urea, night soil, animal manure
Out-sighted crop nutrients	Aerosol dust, rain and contaminated irrigation water
Soil properties	
Soil type (texture)	Silt loam
Bulk density (surface and subsurface 0.07 m depth)	1.29–1.43
pH (0.15–0.30 m surface and subsurface)	7.82–7.92
EC (dsm^{-1})	1.28–1.29
Organic matter 0.15–0.30 m (%)	5.73–5. 37

[a] Village and fields under study area, measured by google earth tools

To address these challenges, this study evaluates nitrogen (N) management strategies by comparing conventional and alternative practices. The treatment combinations were selected based on their relevance to regional farming practices, feasibility, and potential to reduce N losses while maintaining crop productivity. Conventional treatments represent commonly used fertilization and irrigation practices, while managed treatments incorporate strategies aimed at improving nitrogen use efficiency. These include adjustments in fertilizer timing, placement, and application methods to mitigate leaching and gaseous losses. This study provides insight into the effectiveness of these management practices, offering recommendations tailored to the Kabul region.

Therefore, this study aims to address these challenges through the following objectives:

(i). Quantify the distribution of applied nitrogen (N) in a typical farming system in the peri-urban land of Kabul.

(ii). Assess and evaluate the efficiency of specific management practices at reducing N losses and improving NUE in a wheat-growing system.

(iii). Quantify the magnitude and timing of N losses through different pathways to determine the effectiveness of strategies in reducing N losses.

(iv). Develop a seasonal N budget for different experimental manipulations within the studied cropping systems.

Through these objectives, this research aims to provide valuable insights into nitrogen (N) management practices that can enhance nutrient use efficiency, reduce nitrogen losses, and improve the overall sustainability of farming systems in the Kabul region of Afghanistan.

2. Materials and methods

2.1. Study area and site selection

The field experiment was conducted in Shewaki, a peri-urban village (N: 34°28′45.96; E: 69°12′54.94) located southeast of Kabul city at an elevation ranging between 1,767 m and 1,786 m above mean sea level (MSL), in the Bagrami District of Kabul Province, Afghanistan (figure 1). The overall characteristics of the village and the dominant farming system in the village are detailed in table 1. The average annual temperature in the region varies between 10 °C and 13 °C, with a relative humidity of approximately 54%, based on climate data from the period 1957 to 1977, as reported by Grieser *et al* [24, 25]. The province receives an average annual precipitation of 300–330 mm, primarily occurring between November and May. From January 2020 to May 2021, the average recorded precipitation was 29.30 mm, and the temperature averaged 14.15 °C, indicating.

2.2. Layout of the experiment and treatments

Spring wheat (*Triticum aestivum* var. Gull (was grown in a replicated, blocked experiment designed to compare ten treatments, grouped into three categories: (A) animal manure, urea, and diammonium phosphate (DAP); (B) night soil (human waste), urea and DAP; and (C) urea and DAP alone (table 2). Within each group, the rates

Table 2. Layout of the experiment and method of inputs applications.

Group	Treatment	Combination (treatment)	Total N kg ha^{-1} (chemical fertilizer + manure/night soil)	Mode of application
A	A_1	−25% AM+50% urea and DAP	132	Managed
	A_2	+25% AM+50% urea and DAP	173	Managed
	A_3	2 t ha^{-1} AM+50% urea and DAP	152	Conventional
B	B_1	−25% NS+50% urea and DAP	91	Managed
	B_2	+25% NS+50 urea and DAP	105	Managed
	B_3	2 t ha^{-1} NS+50% urea and DAP	98	Conventional
C	C_1	−25% of urea and DAP	103	Managed
	C_2	+25% of urea and DAP	172	Managed
	C_3	250 kg ha^{-1} urea and 125 kg ha^{-1} DAP	138	Conventional
Control	Unamended Control	No amendment of fertilizer and/or manure etc	0	Not applied

Note: Treatment combinations were selected based on conventional (A_3, B_3 and C_3) and managed (A_1, A_2, B_1, B_2, C_1, and C_2) practices in the Kabul region, as detailed in the treatment section of the manuscript. Managed treatments include optimized nutrient strategies (e.g., incorporating organic amendments like 2 t animal manure (AM) + 50% of standard chemical fertilizer dose (250 kg ha^{-1} urea and 120 kg ha^{-1} diammonium phosphate; DAP) and 2 t ha^{-1} night soil (NS) + 50% standard chemical fertilizer dose (250 kg ha^{-1} urea and 125 kg ha^{-1} DAP) to enhance nitrogen use efficiency and sustainability.

of nitrogen (N) inputs were varied by ±25%, and different fertilizer placements were compared. These included a 10 cm deep placement (managed methods: A_1, A_2, B_1, B_2, C_1, and C_2) involved tillage using a hand hoe to create a furrow beside the crop rows, where the fertilizer was placed and then covered with soil. The conventional method (A_3, B_3, and C_3) used by farmers involved broadcasting the fertilizer across the field.

All manures were applied at the onset of wheat crop tillering. These treatments were compared with a zero-N applied control, where no nitrogen was intentionally added. However, it is important to note that residual nitrogen from irrigation water and dust was present, though it could not be controlled. Each treatment was replicated three times, with each plot measuring 15 × 1.2 meters. The distance between plots was set at 30 cm, with the distance between replicates maintained at 50 cm.

Irrigation for wheat in the Kabul region typically depends on seasonal rainfall and the availability of water in streams. During the spring growing season, water requirements for wheat are primarily met by rainfall, supplemented with irrigation as needed. In years with sufficient rainfall, irrigation may not be required, while in drier periods, farmers typically irrigate 4–6 times during the growing season, with an interval 10 to 12 days between irrigation. This irrigation schedule can be influenced by high relative humidity and rainfall in the region, which also affect the crop's water requirements. Flood irrigation was used for this experiment, consistent with local farming practices, to ensure uniform moisture across the plots.

2.3. Sampling and measurement

Irrigation water was sampled at each irrigation event and pooled. To prevent biochemical degradation, one drop of concentrated (32%) HCl was added to the water samples before storing them in polyethylene (PE) bottles at a temperature below 4 °C until analysis of total N. The nitrogen content of the chemical fertilizers, urea (46% N) and diammonium phosphate (DAP) (18% N), was provided by the manufacturers. To measure manure N, five sub-samples from the manure heap were collected using a 5 × 20 cm soil sampler to a depth of 0.2 m, pooled, air-dried at room temperature for 48 h, and ground with a mill (MPD102, Biobase China). These samples were stored in PE bottles until analysis for dry matter (DM) and total N.

Dust samples were collected every month for the entire period using three plastic pans covered with mesh to avoid contamination from bird excreta. These pans were mounted on individual columns at 2 m above the field surface and placed around the experimental field to monitor dust deposition. While the design aimed to capture dust coming into the field, we acknowledge that wind-induced surface soil disturbances could have influenced the measurements at this height. After filtering and drying the dust samples at room temperature, they were weighed and sealed in nylon plastic bags for subsequent analysis.

Prior to wheat cultivation, surface (0.0–0.15 m) and subsurface (0.15–0.30 m) soil samples were collected from each experimental plot at five locations in February and pooled. Individual samples were spread out on paper and air-dried in the shade at room temperature. Samples were stored in PE bottles before chemical analysis. Roots and other residues were removed by passing the samples through a 2-mm mesh sieve. Additional soil samples were stored below 4 °C in Ziplock bags and transferred to the lab for NO_3^- and NH_4^+ analysis. To determine soil moisture content and bulk density, additional samples were taken with a 7 × 7 cm auger from surface (0.0–0.15 m) and subsurface (0.15–0.30 m) soil. These samples were weighed, dried at 105 °C, and reweighed [26].

At crop maturity, measurements were recorded for the yield and yield components of wheat, including plant height (PH), number of tillers (NT), number of productive tillers (NPT), number of spikelets per spike (NSPS), spike length (SL), number of grains per spikelet (NGSL), and number of grains per spike (NGS). These measurements were randomly selected from ten plants in each plot and averaged. During the harvest, from harvested mound, 10 random fistfuls of grain were taken, and 1000 grains were counted and weighed. Additionally, approximately 300 g of fresh weight (grain and straw of wheat) were harvested from five points in the field, pooled, weighed, dried to a constant weight at 60 °C for 48 h, and weighed again for moisture content correction. Subsamples of dried yield components were ground with a mill (MPD102, Biobase China) to a size of 0.5 mm, and sealed in polyethylene Ziplock bags until analysis of N.

2.4. Physico-chemical analyses

Soil textural classes at depths of 0.0–0.15 m and 0.15–0.30 m were determined using the hydrometer method as described in the ICARDA manual for soil, plant, and water analysis [27]. Soil pH and electrical conductivity (EC) at these depths were measured with a portable pH meter (HI9811-5 Portable pH/EC/TDS/temperature meter, Hanna, Romania) in a 1:5 soil-water suspension (5 grams of soil and 25 milliliters (ml) of distilled water). Total soil N was determined using an Automatic Kjeldahl Distillation Unit (Model K9840), following the ICARDA manual for soil, plant, and water analysis [27].

Nitrate (NO_3^-) and NH_4^+ concentrations were measured by mixing 10 g of fresh soil with 40 ml of 0.0125 mol l^{-1} calcium chloride ($CaCl_2{\cdot}2H_2O$) and shaking for one hour. The samples were then filtered using filter paper (MN 615 ¼) for analysis. Total N in manure and dust samples was also analyzed with the Automatic Kjeldahl Distillation Unit, as outlined in the ICARDA manual [27].

Additionally, adherent sand particles were analyzed for hydrochloric acid (HCl)-insoluble ash according to Naumann and Bassler [28]. Soil organic matter (SOM) was measured using the method described by Close and Menke [29], with a conversion factor of 1.724 applied to convert organic matter to organic carbon (C_{org}), based on the assumption that organic matter (OM) contains 58% of C_{org} [30]. Total N in irrigation water samples was analyzed using the same Automatic Kjeldahl Distillation Unit referenced earlier [27]. The total N in crop samples was also determined using this unit, as specified in the ICARDA Manual [27].

2.4.1. Estimation of NH_3 emissions

Ammonia (NH_3) emissions were measured using the boric acid trap method. Three acrylic chambers (30 cm length, 20 cm breadth, and 50 cm height) were placed on the soil surface simultaneously within each replication to ensure consistent measurements of NH_3 emissions. The chambers were used to sample emissions from the same area during each sampling period. After completing the measurements for one replication, the process was repeated for the second and third replications to ensure accuracy and replicate conditions.

Ammonia emitted from the soil surface was drawn through a 0.1% boric acid solution using a suction pump with a flow rate of 3 l min^{-1} for 30 min. The flow rate and sampling duration were selected base on previous studies to minimize potential NH_3 adsorption to the chamber walls while ensure sufficient chamber exchange. To minimize potential biases from NH_3 adsorption due to fluctuations in temperature and humidity, sampling was conducted during periods of stable environmental conditions, specifically between 10:00 AM and 4:00 PM for seven consecutive days following manure application.

Note: Gaseous NH_3 concentrations were not measured directly. Instead, NH_3-N concentrations were calculated based on the amount of sulfuric acid consumed during the titration (mg m^{-2}). The volatilized NH_3 reacts with boric acid in the solution to form ammonium borate, which is then titrated with standard sulfuric acid (H_2SO_4). One mole of sulfuric acid is required to neutralize two moles of NH_3. Quantitative determination of NH_3 was performed by titration with standard sulfuric acid (H_2SO_4) [31, 32].

2.4.1.1. Formula for NH_3 flux calculation

The amount of ammonia flux from a unit area of soil was estimated using the following formula, adapted from Bremner (32):

$$\mathrm{NH_4-N\ \ volatilized(mg/m^2/30\ \ minutes)} = \mathrm{X} \times 0.000014 \times 1000/\mathrm{A}$$

Where:

X = amount of sulfuric acid consumed (ml), A = area of soil surface covered by the chamber (m^2), 0.000014 = conversion factor for sulfuric acid consumption to NH_3-N (mg), and 1000 = unit conversion factor to obtain results in mg/m^2 per 30 min.

It is assumed that one mole of sulfuric acid (H_2SO_4) is required to neutralize one mole of ammonium (NH_4^+), which is formed from the reaction of ammonia (NH_3) with boric acid in the solution.

2.4.2. Estimation of $NO_3^- - N$ and $NH_4^+ - N$ leaching

For the leaching study, 10 out of 30 experimental plots (one replication) planted with wheat were selected, including treatments A_1, A_2, C_1, B_1, B_2, C_2, A_3, B_3, C_3, and unamended control. PVC cartridges (three capsules per plot), with a surface area of 19.625 cm^2 and a nylon net at the bottom, were filled with an ion-exchange resin-sand mixture, following procedure from previous studies [33–35]. The cartridges were placed below the subsurface layer at a depth of 0.45 m from April to July 2021.

After extraction, the resin-sand mixture was divided into five layers (L_1 to L_5), each approximately 10 mm thick, and stored at below 4 °C until analysis. For ion extraction, 10 ± 0.5 g of the pooled layer were placed into 250-ml plastic bottles, mixed with 100 ml of a 0.5 M NaCl extractant, and shaken horizontally for one hour. Sample were extracted eight times; extracts 1 to 4, 5 to 6, and 7 to 8 were pooled together, and a 20-ml sub-samples frozen for later analysis of $NO_3^- - N$ and $NH_4^+ - N$ using an inductively coupled plasma spectrometer (ICP; Model Spectro-Flame, Spectro Analytica Instruments GmbH & Co. KG, Kleve, Germany). Duplicate sand samples (10 g pooled) were extracted similarly and served as blanks. Nutrients concentrations were then converted to kg ha^{-1} $season^{-1}$.

2.5. Calculations of nutrient balance and apparent nutrient use efficiencies

For each plot, partial (horizontal) N balances were calculated based on the quantity of N inputs and outputs (inorganic and organic fertilizers, dust, and irrigation water applied *versus* crop biomass harvested) per hectare. Wherever applicable, crop residues were returned to the plot and therefore not considered for the calculation of N outputs. N fluxes were estimated by multiplying the mass of material by its N concentrations (equation (1); [36].

$$F = \sum_{i=1}^{n} Q_i C_i \tag{1}$$

where F is the total N flow (input or output) over the period of measurement, n is the number of events (application of fertilizer, irrigation water, dust, or harvested crop product), Q_i is the quantity of plant DM at event i, and C_i is the N concentration in the plant DM at event i.

The N balance equation for each plot was expressed as:

$$\Delta PE = IE - OE \tag{2}$$

where ΔP_E, I_E and O_E stand for each change in the pool, the input and the output of element E [36].

Applying equation (2), the input flows for N were estimated for dust after sowing (D_E, though often negligible), irrigation water (IW_E), and fertilizers (F_E). Similarly, the output flows were assessed for harvested crops (H_E) . If ΔP_E is the net change in soil storage of element E ($\Delta soil_E$), equation (2) can be written as:

$$\Delta SoilE = DE + IWE + FE - HE \tag{3}$$

This approach neglected rain N deposition as it was likely to have been small in Kabul, as well as runoff on the well-leveled fields, N_2-fixation in non-symbiotic crops that typically ranges from 25 kg N ha^{-1} $year^{-1}$ [37], and the likely large volatilization of C, which unfortunately could not be measured under the local conditions. Calculations were done for the wheat crop from planting to harvest over 4–5 months. [35].

Apparent use efficiencies for N, was calculated according to Wang *et al* [38] as:

$$UE = \frac{\sum O}{\sum I} x100 \tag{4}$$

where UE denotes apparent nutrient use efficiency, O stands for the nutrient output, and I is the nutrient input.

Partial Factor Productivity was calculated according to equation (5).

$$PFP = \frac{\text{Above ground dry matter}}{\text{Total N input in manure or fertilizer}} \times 100 \tag{5}$$

2.6. Statistical analyses

Multivariate/univariate analyses of variance (MANOVA) were performed using SPSS (Version 23.0, SPSS Inc., Chicago, IL, USA) to determine the significance of differences between the 10 treatments for nutrient inputs, outputs, horizontal fluxes, UE, PFP, soil chemical properties (soil pH, EC, OM, C_{org}, total N, NO_3, NH_4, and physical properties (BD, and soil texture) [35].

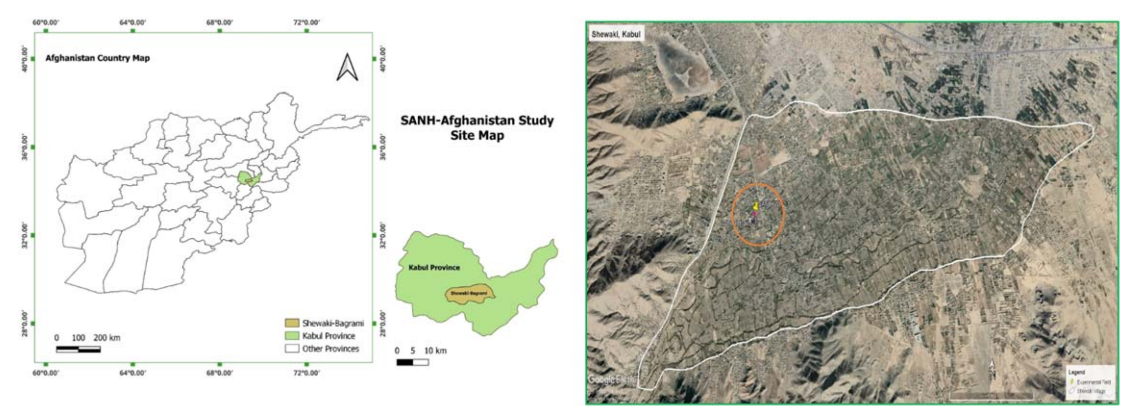

Figure 1. Map of Afghanistan emphasizing Kabul Province, with Shewaki Village and Research Site Highlighted.

3. Experimental results

3.1. Surface (0.0–0.15 m) and subsurface (0.15–0.30 m) soil physical and chemical properties

The soil at the experimental site was classified as Fluvisol [39], formed from alluvial deposits. The surface soil (0.0–0.15 m) had a texture composed of 17.29% sand, 66.10% silt, and 16.65% clay, while the subsurface layer (0.15–0.30 m), contained slightly more sand (19.5%) and less clay (15.7%). The calcium carbonate ($CaCO_3$) concentration was 11%, as reported by Safi *et al* [35].

In this initial assessment, total nitrogen (N), organic matter (OM), and organic carbon (Corg), concentrations showed no statistical differences across treatments (tables 3, 4), Likewise, available phosphorus (P), Potassium (K), pH, electrical conductivity (EC), and soil bulk density (BD) showed no significant variations among treatments.

Although slight differences were observed in nitrate nitrogen ($NO_3^- - N$) and ammonium nitrogen ($NH_4^+ - N$) in surface and subsurface soil before cultivation, these variations were not statistically significant ($P > 0.05$) (table 5). This indicates that initial nitrogen availability was relatively uniform across treatments, minimizing potential bias in subsequent assessments.

3.2. N inputs and losses

Farming in Shewaki village is characterized by significant nitrogen (N) inputs, prilimarily driven by the use of organic amendments and synthetic fertilizers. Typically (conventionally), farmers apply 2 t ha^{-1} of either night soil (NS) or animal manure (AM), along with 50% of the standard nitrogen dose (137.5 kg N ha^{-1}) from urea and diammonium phosphate (DAP). In this study, nitrogen inputs were adjusted relative to the farmer's standard practices by applying treatments with 25% less (A_1, B_1, and C_1) and 25% more (B_2, A_2, and C_2) than standard nitrogen dose. These adjustments allowed for a comparison of nitrogen dynamics across different input levels. Additionally, all plots, including the unamended control, received a uniform quantity of N through irrigation water (133 kg ha^{-1}) and atmospheric dust deposition (5 kg ha^{-1}) over the growing season (table 6).

Ammonia (NH_3) losses via volatilization were measured for seven days post-treatment in the A_2, A_3, and control treatments. Significant nitrogen losses were observed, with volatilization rates of 55%, 32% and 13% across these treatments, respectively ($P < 0.05$) (figure 2). These results indicate substantial differences in NH_3 volatilization between treatments, with the highest losses recorded in A_2, suggesting a strong influence of treatment levels on volatilization dynamics. However, NH_3 volatilization was not measured in the other treatments due to instrumental constraints, limiting a broader comparison.

Resin-based nitrate $NO_3^-{-}N$ leaching across all treatments averaged 39 kg ha^{-1} season^{-1}, while ammonium ($NH_4^+ - N$) leaching averaged 34 kg ha^{-1} season^{-1} (figure 3). For the animal manure treatment (A), $NO_3^-{-}N$ leaching was highest in A_1 at 49 kg N ha^{-1} (39%), followed by A_3 at 40 kg N ha^{-1} (32%). $NH_4^+{-}N$ leaching was greatest in A_3 at 36 kg N ha^{-1} (46%) followed by A_1 and A_2 at 25 and 18 kg N ha^{-1} (23 and 16%), respectively.

For the night soil treatments (B), $NO_3^-{-}N$ leaching peaked in B_1 at 60 kg N ha^{-1}: 53%, followed by B_3 at 30 kg N ha^{-1} (27%) and B_2 at 23 kg N ha^{-1} (20%). $NH_4^+{-}N$ leaching was highest in B_3, at 68 kg N ha^{-1} (45%), followed by B_1 at 47 kg N ha^{-1} and B_2 at 35 kg N ha^{-1} (31% and 23%, respectively).

In the urea and DAP treatments (C), $NO_3^-{-}N$ leaching was highest in C_3 at 53 kg N ha^{-1} (44%), followed by C_1 and C_2 at 35 and 32 kg N ha^{-1} (42 and 12%, respectively). Similarly, $NH_4^+{-}N$ leaching was also highest in C_3 at 50 kg N ha^{-1} (46%), followed by C_1 and C_2 at 45 and 13 kg N ha^{-1} (42 and 12%, respectively). The control

Table 3. Indigenous soil physicochemical properties (total nitrogen (N), plant-available phosphorus (P), potassium (K), organic matter (OM), organic carbon (C_{org}), bulk density (BD), and electrical conductivity (EC) of experimental plots at 0.0–0.15 m depth before wheat cultivation in Shewaki, Kabul, Afghanistan.

Soil properties (0.0–0.15 m)	A_1	A_2	A_3	B_1	B_2	B_3	C_1	C_2	C_3	Control
OM (%)	5.65 ^{a} (±0.80)	5.41 ^{a} (±0.24)	5.57 ^{a} (±0.38)	5.39 ^{a} (±0.84)	6.59 ^{a} (±2.08)	5.82 ^{a} (±0.35)	5.35 ^{a} (±0.12)	5.37 ^{a} (±1.32)	5.82 ^{a} (±1.02)	6.33 ^{a} (±0.43)
C_{org} (%)	3.28 ^{a} (±0.49)	3.14 ^{a} (±0.14)	3.23 ^{a} (±0.22)	3.13 ^{a} (±0.49)	3.82 ^{a} (±1.29)	3.38 ^{a} (±0.20)	3.11 ^{a} (±0.07)	3.12 ^{a} (±0.77)	3.8 ^{a} (±0.59)	3.67 ^{a} (±0.25)
N (%)	0.41^{a} (±0.08)	0.62^{a} (±0.31)	0.47^{a} (±0.03)	0.38^{a} (±0.11)	0.39^{a} (±0.11)	0.78^{a} (±0.69)	0.57^{a} (±0.05)	0.39^{a} (±0.06)	0.43^{a} (±0.07)	0.55^{a} (±0.36)
P (%)	0.02^{a} (±0.01)	0.01^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)
K (%)	0.37^{a} (±0.10)	0.34^{a} (±0.04)	0.33^{a} (±0.08)	0.33^{a} (±0.08)	0.30^{a} (±0.06)	0.33^{a} (±0.03)	0.36^{a} (±0.09)	0.37^{a} (±0.05)	0.35^{a} (±0.07)	0.35^{a} (±0.08)
BD	1.31^{a} (±0.08)	1.27^{a} (±0.03)	1.29^{a} (±0.04)	1.26^{a} (±0.03)	1.30^{a} (±0.03)	1.30^{a} (±0.05)	1.30^{a} (±0.02)	1.30^{a} (±0.03)	1.27^{a} (±0.04)	1.28^{a} (±0.02)
pH	7.67^{ab} (±0.23)	7.73^{a} (±0.15)	7.83^{a} (±0.25)	7.80^{a} (±0.10)	8.00^{ac} (±0.17)	7.90^{a} (±0.17)	7.80^{a} (±0.10)	7.80^{a} (±0.10)	7.90^{a} (±0.17)	7.73^{a} (±0.15)
EC (dSm^{-1})	1.29^{a} (±0.11)	1.22^{a} (±0.07)	1.22^{a} (±0.07)	1.33^{a} (±0.05)	1.33^{a} (±0.05)	1.26^{a} (±0.07)	1.33^{a} (±0.05)	1.26^{a} (±0.07)	1.29^{a} (±0.11)	1.29^{a} (±0.11)

+ Different letters within a row indicate significant differences ($P < 0.05$) between treatments. Data show means ± one standard deviation. Treatment details: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure + 50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil + 50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil + 50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and 125 kg ha^{-1}DAP).

Table 4. Indigenous soil physicochemical properties (total nitrogen (N), plant-available phosphorus (P), potassium (K), organic matter (OM), organic carbon (C_{org}), bulk density (BD), and electrical conductivity (EC)) of experimental plots at 0.15–0.30 m depth before wheat cultivation in Shewaki, Kabul, Afghanistan.

Soil properties (0.15–0.30 m)	A_1	A_2	A_3	B_1	B_2	B_3	C_1	C_2	C_3	Control
OM (%)	5.11^{a}(±0.74)	5.23^{a}(±0.0.47)	5.41^{abc}(±0.33)	4.76^{ad}(±0.58)	5.50^{abc}(±.0.07)	4.97^{a}(±0.18)	5.66^{ab}(±0.36)	5.08^{abc}(±0.96)	6.20^{b}(±0.73)	5.74^{c} (±0.37)
C (%)	2.96^{a}(±0.43)	3.03^{a} (±0.27)	3.14^{abc} (±0.19	2.76^{ad} (±0.34)	3.19^{abc} (±0.04)	2.88^{a} (±0.11)	3.28^{ab} (±0.21)	2.95^{abc} (±0.55)	3.60^{b} (±0.42)	3.33^{c}(±0.22)
N (%)	0.48^{a} (±0.18)	0.33^{a} (±0.02)	0.37^{a} (±0.04)	0.40^{a} (±0.09)	0.40^{a} (±0.19)	0.56^{a} (±0.18)	0.51^{a} (±0.18)	0.50^{a} (±0.16)	0.48^{a} (±0.02)	0.49^{a} (±0.12)
P (%)	0.02^{a} (±0.01)	0.01^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)	0.01^{a} (±0.01)	0.02^{a} (±0.01)	0.02^{a} (±0.01)
K (%)	0.56^{a} (±0.05)	0.52^{ab} (±0.01)	0.54^{acd} (±0.01)	0.51^{bc} (±0.02)	0.49^{b} (±0.03)	0.54^{cda} (±0.03)	0.51^{d} (±0.02)	0.53^{a} (±0.02)	0.54^{acd} (±0.01)	0.53^{abcd} (±0.01)
BD	1.49^{a} (±0.14)	1.46^{a} (±0.03)	1.39^{a} (±0.06)	1.38^{a} (±0.07)	1.46^{a} (±0.12)	1.46^{a}(±0.18)	1.40^{a} (±0.10)	1.43^{a} (±0.18)	1.42^{a} (±0.05)	1.39^{a} (±0.02)
pH	7.93^{a} (±0.06)	7.97^{a} (±0.06)	7.90^{acd} (±0.00)	7.90^{acd} (±0.00)	8.07^{b} (±0.06)	7.90^{acd} (±0.00)	7.90^{acd} (±0.10)	7.83^{bc} (±0.06)	7.83^{cd} (±0.06)	7.93^{a} (±0.06)
EC (dSm^{-1})	1.22^{a} (±0.14)	1.22^{a} (±0.14)	1.31^{a} (±0.14)	1.31^{a} (±0.14)	1.31^{a} (±0.14)	1.31^{a} (±0.14)	1.31^{a} (±0.14)	1.31^{a} (±0.14)	1.31^{a} (±0.14)	1.31^{a} (±0.14)

+ Different letters within a row indicate significant differences ($P < 0.05$) between treatments. Data show means ± one standard deviation. Treatment details: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure + 50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil + 50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil + 50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and 125 kg ha^{-1} DAP).

Table 5. NO_3^-−N and NH_4^+−N concentrations (mg kg^{-1}) in fresh soil at depths of 0.0–0.15 m and 0.15–0.30 m prior to wheat cultivation in the experimental field.

Nr (mg kg^{-1})	Soil Depth (m)	A_1	A_2	A_3	B_1	B_2	B_3	C_1	C_2	C_3	Control
NO_3	0.0–0.15	92.83(±44.87)	77.43(±54.82)	60.52(±25.30)	59.09(±21.20)	50.76(±17.97)	54.88(±10.18)	51.43(±10.14)	63.35(±27.89)	51.81(±33.68)	74.75(± 22.40)
NH_4		0.5(±0.01)	0.31(±0.03)	1.21(±1.48)	1.05(±1.23)	0.59(±0.56)	1.39(±1.03)	1.13(±1.35)	1.00(±1.22)	0.99(±1.25)	1.01(±1.16)
NO_3	0.15–0.30	62.96(±10.14)	47.96(±0.95)	52.39(±23.52)	59.05(±30.53)	49.54(±19.12)	76.73(±30.06)	45.55(±13.13)	46.08(±25.01)	63.55(±22.89)	88.95(±46.44)
NH_4		1.66(±2.02)	0.38(±0.03)	1.12(±1.16)	0.48(±0.15)	1.56(±0.97)	0.90(±0.76)	0.90(±0.89)	0.44(±0.04)	0.84(±0.57)	1.48(±1.31)

Data show means ± one standard deviation. Details of the treatments are: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure+50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil+50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil + 50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and 125 kg ha^{-1} DAP).

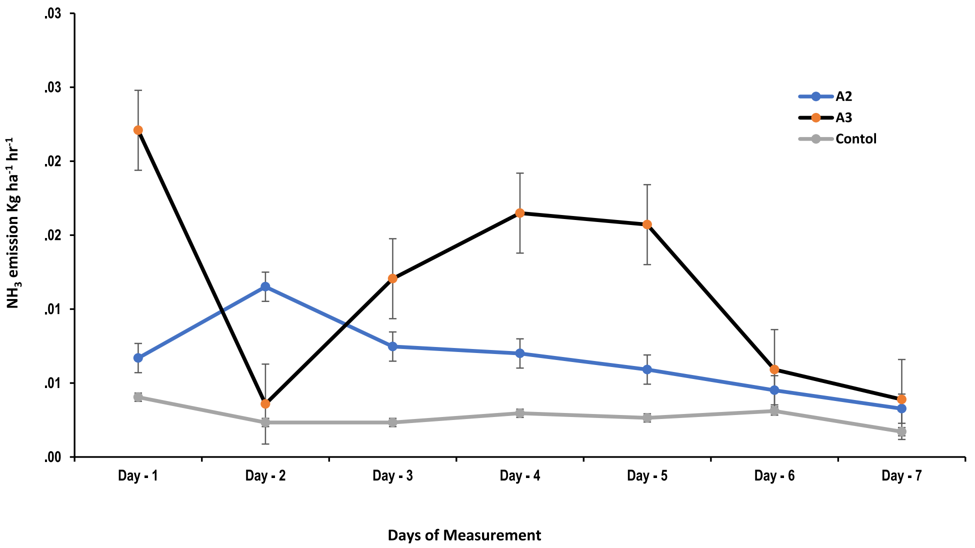

Figure 2. Ammonia (NH_3) emissions per day per 30 min from the wheat experimental field, typical farmer practice treatment, managed, and control plots (n = 3) in Shewaki village of Kabul, Afghanistan. Details of the treatments: A_2 (+25% animal manure + 50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), and control (N not applied).

Table 6. Inputs of N, P, and K (kg ha^{-1}) via applied manures (animal manure and night soil), chemical fertilizers (urea and DAP), and imported N via irrigation water and precipitation of aerosol dust throughout the growing season of the wheat crops.

							NPK added by irrigation water and aerosol dust					
Treatments	Man. N kg ha^{-1}	Man. P kg ha^{-1}	Man. K kg ha^{-1}	Che.N kg ha^{-1}	Che. P kg ha^{-1}	Che. K kg ha^{-1}	Irr.N kg ha^{-1}	Irr. P kg ha^{-1}	Irr. K kg ha^{-1}	Dust N Kg ha^{-1}	Dust P Kg ha^{-1}	Dust K Kg ha^{-1}
A_1	62.79	0.12	8.51	68.75	28.75	0.00	132.61	14.17	82.90	4.85	0.05	1.76
A_2	104.66	0.20	14.18	68.75	28.75	0.00	132.61	14.17	82.90	4.85	0.05	1.76
A_3	83.72	0.16	11.34	68.75	28.75	0.00	132.61	14.17	82.90	4.85	0.05	1.76
B_1	21.84	0.11	3.79	68.75	28.75	0.00	132.61	14.17	82.90	4.85	0.05	1.76
B_2	36.40	0.18	6.32	68.75	28.75	0.00	132.61	14.17	82.90	4.85	0.05	1.76
B_3	29.12	0.14	5.06	68.75	28.75	0.00	132.61	14.17	82.90	4.85	0.05	1.76
C_1	0.00	0.00	0.00	103.13	43.13	0.00	132.61	14.17	82.90	4.85	0.05	1.76
C_2	0.00	0.00	0.00	171.88	71.88	0.00	132.61	14.17	82.90	4.85	0.05	1.76
C_3	0.00	0.00	0.00	137.50	57.50	0.00	132.61	14.17	82.90	4.85	0.05	1.76
Control	0.00	0.00	0.00	0.00	0.00	0.00	132.61	14.17	82.90	4.85	0.05	1.76

Details of the treatments are: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure+50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil+50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil + 50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and 125 kg ha^{-1} DAP).

treatment exhibited low leaching of NO_3^-−N (28 kg N ha^{-1}) and zero (0) NH_4^+−N leaching, although this was still more than B_2 treatment.

The total NO_3^-−N leaching across all 10 treatments was 386.15 kg ha^{-1}, with the highest NO_3^-−N leaching occurring in B_1 at 60 kg ha^{-1}, contributing to the largest portion of NO_3^-−N losses. The total NH_4^+−N leaching across all treatments was 336.76 kg ha^{-1}, with the highest observed in B_3, which accounted for 20.23% of the total NH_4^+−N leaching, higher by 68 kg ha^{-1} than other treatments. These findings highlight the relative contribution of leaching to the total nitrogen losses, with clear differences in leaching dynamics across treatments.

However, statistical significance was not assessed for leaching due to resource limitations. While leaching losses varied between treatments, with B_1 exhibiting the highest NO_3^-−N leaching and B_3 showing the highest NH_4^+−N leaching, statistical comparisons were not made due to limited replication and resources. Therefore, although relative differences are presented, these values were not statistically tested for significance across treatments.

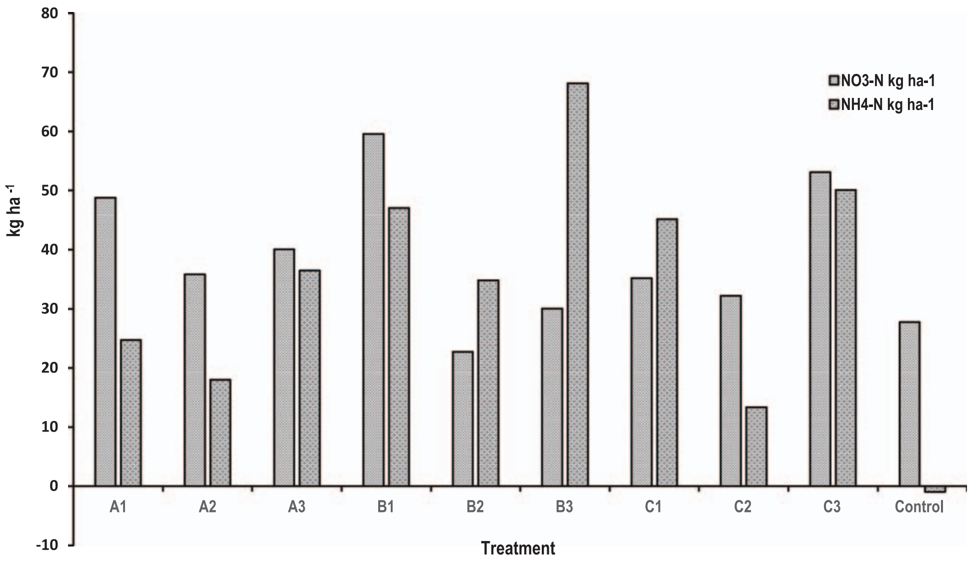

Figure 3. Nitrate- N (NO_3^-−N) and Ammonium- N (NH_4^+−N) leaching under different managed and typical farmer practice wheat treatment in Shewaki village of Kabul, Afghanistan in 2021. Details of the treatments are: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure+50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil+50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil + 50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and 125 kg ha^{-1} DAP).

3.3. N Outputs (harvested)

Plant heights (PH) across the treatments ranged from 91 to 95 cm, with the maximum observed in the A_3 treatment, followed closely by A_2. The spike lengths (SL) varied between 9.56 and 10.53 cm, with A_2 having the longest spike length at 10.5 cm, while B_2 was slightly behind at 10.4 cm). B_3 exhibited the shortest spike length. The number of tillers (NT) was highest in B_2 and B_3 (2.7 each), whereas C_3 had the fewest. Non-productive tillers (NPT) ranged from 1.6 to 2.2, with the peak in B_2, followed by B_3 treatments (2.0), and the control showing 1.9. The number of spikelets per spike (NSPS) varied from 17.8 to 18.7, with A_2 having the maximum and B_3 minimum. The number of grains per spikelet (NGSL) ranged from 3.0 to 3.6, with A_2 again showing the highest and A_3 the lowest. The weight of 1000 grains (GW) varied between 28.6 and 43.7 g, with C_3 at the top (43.7 g), followed closely by A_2 (43.5 g). These differences were statistically significant ($P < 0.05$) (table 7).

Average seasonal N removal across the A, B, and C treatments exhibited variation. Managed treatments C_1 and B_2 recorded the highest yields (241.5 and 241.4 kg N ha^{-1}, respectively), followed by B_3 (218 kg N ha^{-1}), A_1, (201 kg ha^{-1}) and C_3 (210 kg N ha^{-1}). Although these treatments showed variation in N removal, the B_2 treatment had the lowest yield at 147.4 kg N ha^{-1}. However, statistical analysis indicated no significant differences in N removal ($P > 0.05$). (figure 4). This suggests that, although trends in N removal were observed, the differences were not statistically significant, meaning we cannot confidently attribute these variations solely to the treatments themselves.

Over the cultivation season, a total positive partial N balance of 451.6 kg N ha^{-1} was noted in the treatments A_1, A_2, B_1, B_2, C_1, C_2, A_3, B_3, and C_3. These values ranged from 162 kg N ha^{-1} in C_2 to −41.4 kg N ha^{-1} in the control, (figure 5). This indicates that most treatments maintained a positive N balance, contributing to nitrogen retention, while the control experienced a negative balance, suggesting nitrogen loss.

3.4. Apparent N-use efficiency and partial factor productivity

Nitrogen-use efficiencies (NUE) of the applied N from animal manure (AM), night soil (NS), urea, diammonium phosphate (DAP), irrigation water, and dust ranged from 47.6% to 130% across the plots. Among the treatments, C_2 exhibited the highest efficiency at 130%, followed by B_2 at 102.3% and A_3 at 99.3%. (figure 6). On other hand, the B_3 treatment showed the lowest NUE at 47.6%. These differences in NUE were statistically significant ($P < 0.05$), indicating that the choice of treatment had a clear impact on the efficiency of nitrogen use.

The Partial Factor Productivity (PFP) varied among treatment groups, with lower N applications (−25%) showing higher PFP compared to conventional practices (figure 7). This suggests that reducing nitrogen inputs may lead to better nitrogen productivity in terms of yield, although these trends should be considered with caution due to the lack of further statistical analysis on the PFP values.

Table 7. Impact of interventions on wheat agronomic parameters: 1000 grain weight (n = 12), plant height (n = 12), spike length (n = 12), number of tillers (n = 12), number of productive tillers (n = 12), number of spikelets per spike (n = 12), number of grains per spikelet (n = 12).

Treatments	1000 grain weight (g) Mean	Plant height (cm) Mean	Spike length (cm) Mean	No of tillers Mean	No of pro. Tillers Mean	No spikelet/ spike Mean	No grain/spikelet Mean
A_1	38.67^{ab} (±3.14)	91.89^{a} (±1.69)	10.04^{a} (±0.59)	2.31^{a} (±0.38)	1.78^{a} (±0.14)	17.89^{a} (±0.53)	3.03^{a} (±0.11)
A_2	43.51^{a} (±6.06)	94.55^{a} (±3.07)	10.53(±0.46)	2.27^{a} (±0.47)	1.88^{ab} (±0.14)	18.73^{a} (±0.31)	3.58^{a} (±0.29)
A_3	41.07^{a} (±9.4)	95.01^{a} (±2.2)	10.14^{a} (±0.39)	2.33^{a} (±0.74)	1.65^{a} (±0.38)	18.12^{a} (±0.32)	2.97^{a} (±0.23)
B_1	35.68^{ab} (±4.02)	91.79^{a} (±1.74)	9.74^{a} (±0.78)	2.30^{a} (±0.52)	1.79^{a} (±0.14)	18.36^{a} (±0.47)	3.18^{a} (±0.24)
B_2	39.84^{a} (±3.15)	92.15^{a} (±1.29)	10.38^{a} (±0.46)	2.73^{a} (±0.31)	2.21^{b}(±0.10)	18.15^{a} (±0.29)	3.3^{a} (±0.34)
B_3	42.22^{a} (±2.74)	93.69^{a} (±0.56)	9.56^{a} (±0.73)	2.72^{a} (±0.6)	2.00^{a} (±0.18)	17.8^{a} (±0.44)	3.15^{a} (±0.28)
C_1	35.58^{a} (±11.1)	90.87^{a} (±5.04)	10.35^{a} (±1.13)	2.30^{a} (±0.29)	1.79^{a} (±0.19)	17.97^{a} (±0.68)	3.03^{a} (±0.32)
C_2	28.62^{b}(±2.17)	91.41^{a} (±1.49)	9.89^{a} (±0.49)	2.27^{a} (±0.42)	1.64^{a} (±0.00)	18.21^{a} (±0.10)	3.03^{a} (±0.23)
C_3	43.72^{a} (±1.22)	92.3^{a} (±0.66)	9.85^{a} (±0.75)	2.21^{a} (±0.52)	1.88^{ab} (±0.19)	17.94^{a} (±0.19)	3.09^{a} (±0.10)
Control	40.11^{a} (±2.28)	91.66^{a} (±9.03)	9.62^{a} (±0.96)	2.34^{a} (±0.51)	1.93^{ab}(±0.30)	17.83^{a} (±0.38)	3.06^{a} (±0.35)

+ Different letters within a column indicate significant differences ($P < 0.05$) between the treatments of wheat experimental trail in Shewaki, Kabul, Afghanistan. Data show means ± one standard deviation. Treatment details: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure + 50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil + 50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil + 50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and 125 kg ha^{-1} DAP).

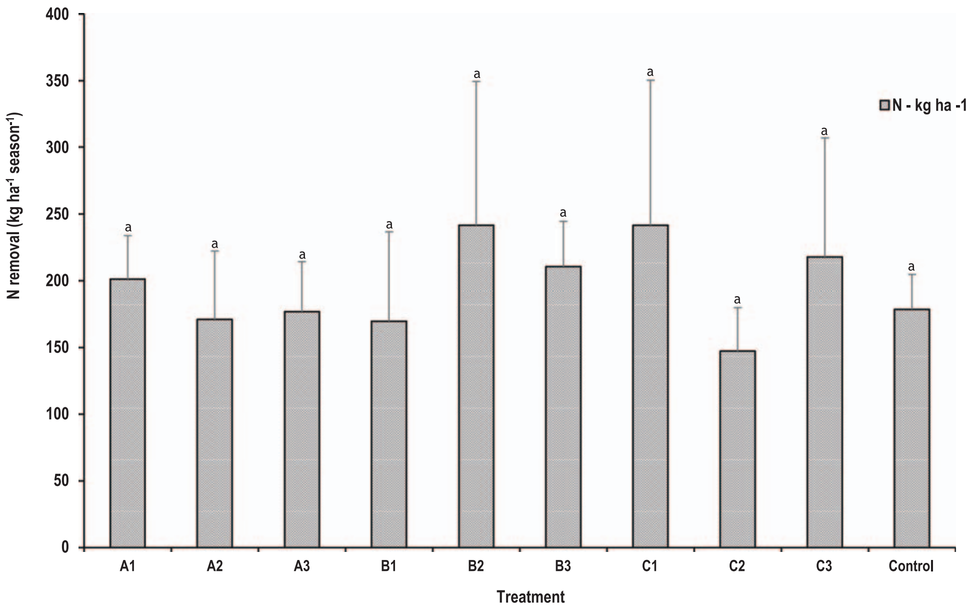

Figure 4. Seasonal (spring season) removal of nitrogen (N) from the experimental trail in Kabul, Afghanistan. Bars show standard deviation of the mean and same letters indicate non-significant differences ($P > 0.05$) between treatments. Details of the treatments are: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure+50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil+50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil +50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and ^{1}25 kg ha^{-1} DAP).

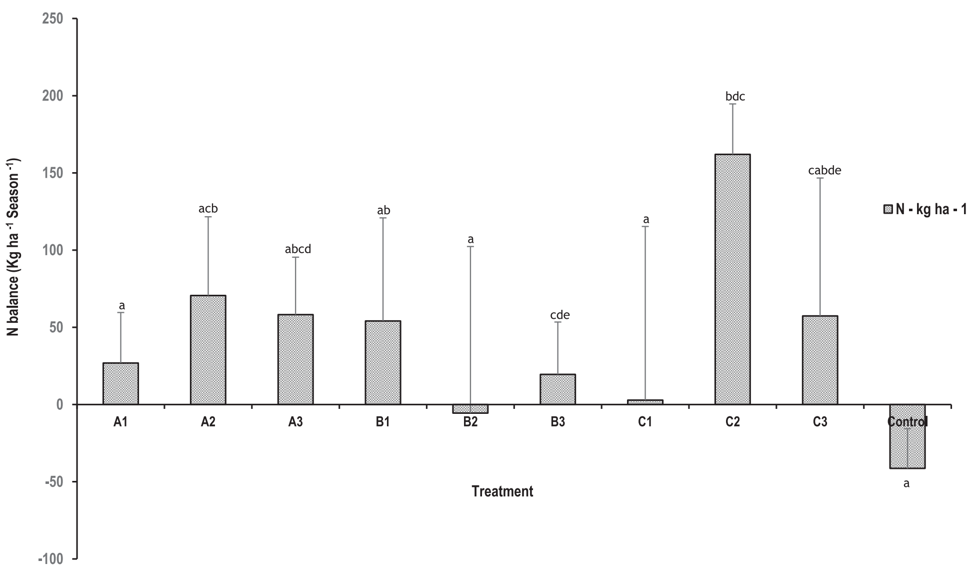

Figure 5. Seasonal horizontal (partial) balances of nitrogen (N) in farming systems of Kabul, Afghanistan ($n = 3$). Bars show standard deviation of the mean, and different letters indicate significant differences ($P < 0.05$) between treatments. Details of the treatments: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure + 50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil + 50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil + 50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and ^{1}25 kg ha^{-1} DAP).

4. Discussion

4.1. N inputs and plant responses

This study underscores the necessity of thoroughly accounting for nitrogen (N) inputs when evaluating sustainable nutrient management practices. Some managed treatments, such as B_2, A_2, and C_2, received significantly higher total N inputs compared to others like B_1, A_1 and C_1 (table 6). The application of ±25%

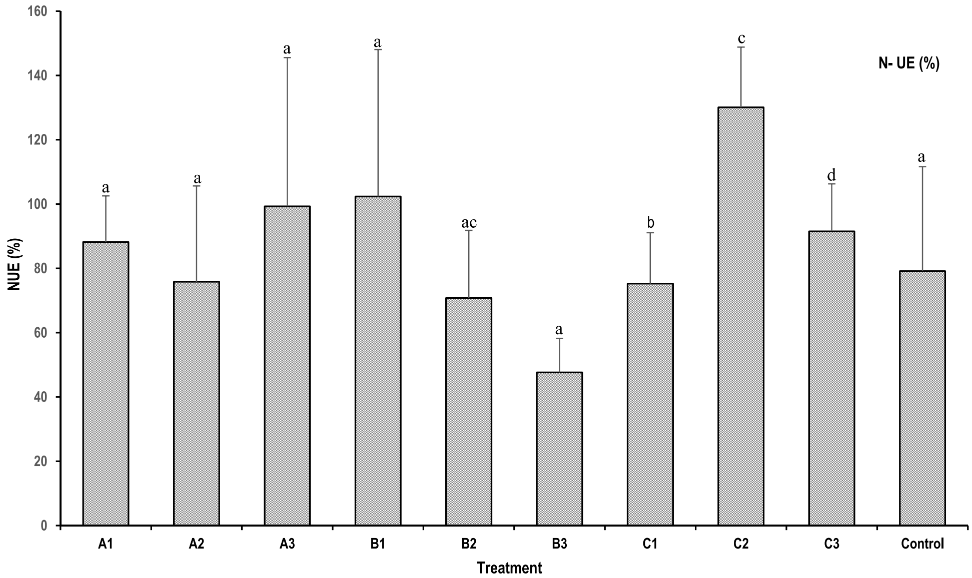

Figure 6. Apparent input use efficiency of nitrogen (N) by wheat crop ($n = 3$) in Shewaki village, Afghanistan. Bars show standard deviation of the mean, and different letters indicate significant differences ($P < 0.05$) between treatments. Details of the treatments: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure + 50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil + 50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil + 50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and [1]25 kg ha^{-1} DAP).

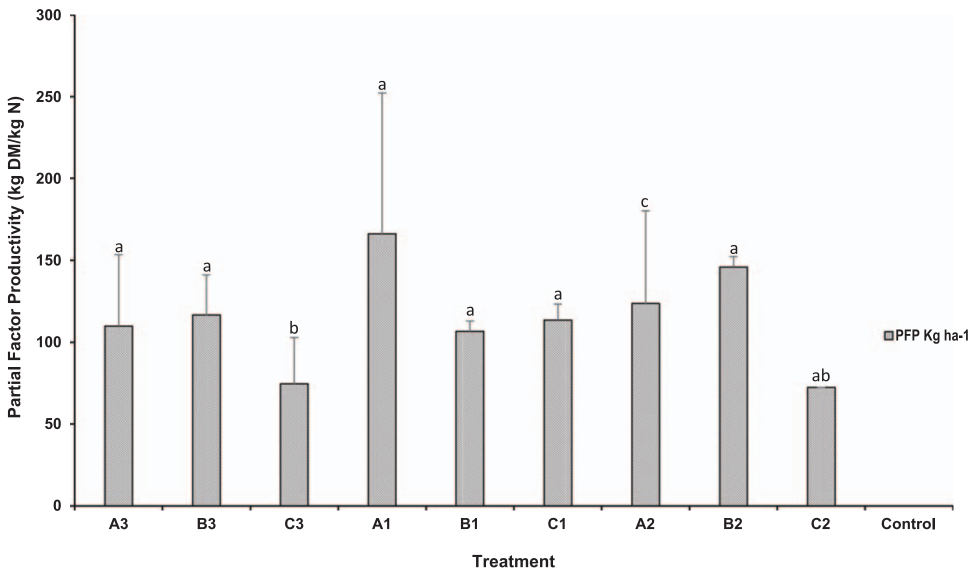

Figure 7. Partial factor productivity of wheat crop ($n = 3$) in Shewaki village, Afghanistan. Bars show standard deviation of the mean, and different letters indicate significant differences ($P < 0.05$) between treatments. Details of the treatments: A_1 (−25% animal manure + 50% urea and DAP), A_2 (+25% animal manure + 50% urea and DAP), A_3 (typical farmers' 2 t ha^{-1} animal manure + 50% urea and DAP), B_1 (−25% night soil + 50% urea and DAP), B_2 (+25% night soil + 50% urea and DAP), B_3 (typical farmers' 2 t ha^{-1} night soil + 50% urea and DAP), C_1 (−25% urea and DAP), C_2 (+25% urea and DAP), C_3 (typical farmers' 250 kg ha^{-1} urea and 125 kg ha^{-1} DAP).

organic and inorganic fertilizers, combined with the deep placement of N sources, was designed to assess the sensitivity of N emissions and NUE to varying N application rates. This approach allowed for the evaluation of N loss patterns in response to agricultural management practices, including N source type, tillage methods, and irrigation management, as recommended by Bakhsh *et al* [40].

In agreement with Strebel *et al* [18] and Fraters *et al* [19], who identified agriculture as a primary contributor to NO_3^- contamination of groundwater, our findings confirm that N leaching can have detrimental environmental impacts [14]. This concern is further emphasized by Cameron *et al* [9], who highlighted the significant environmental and health risks associated with NO_3^- leaching. Our results align with those of Houben *et al* [10], who reported that groundwater in Kabul contains $NO_3^- - N$ levels reaching from 20 to 80 mg l^{-1}.

Leaching losses from both conventional farming practices and the managed experimental plots in this study were significant, ranging from 23 to 60 kg $NO_3^- - N$ ha^{-1} and 5 to 68 kg of $NH_4^+ - N$ ha^{-1} across various experimental treatments. The differences in leaching between managed and conventional treatments highlight the impact of our interventions. However, the leaching rates observed in this study were higher than those reported by Predetova *et al* [41] (5.9 kg N ha^{-1}), and Strok *et al* [42] (32 Kg N ha^{-1}), likely due to the combined impact of groundwater contamination in Shewaki, as reported by Houben *et al* [10], and elevated reactive nitrogen (N_r) losses.

Ammonia (NH_3) emissions in the conventional farmer practice treatments involving surface application (A_3) reached 0.08 kg ha^{-1} h^{-1}, which was 0.05 kg ha^{-1} higher than emissions from the managed subsurface treatment (A_2). This finding aligns with NH_3 emissions observed by Jing *et al* [14], suggesting that volatilization was reduced due to the incorporation of nitrogen (N) into the soil. The emissions from the unfertilized control treatment were 0.02 kg ha^{-1} h^{-1} NH_3.

It is important to note that NH_3 emissions in Shewaki village were likely short-lived due to rapid losses through volatilization and plant uptake from the soil's NH_4 pool. Additionally, the low winter temperatures in Kabul likely moderated nitrogen and carbon (C) emissions, including NH_4^+–N, NO_3^-–N, CH_4–C, and CO_2–C. Based on data from urban peri-urban agriculture (UPA) in Niamey [34], the annual emissions are estimated to be 27–46 kg N ha^{-1} yr^{-1} and 6–10 t C $ha^{-1}yr^{-1}$, approximately 30–50% of emission levels reported in similar UPA vegetable gardens [35].

4.2. N outputs (harvested)

The yield and yield component parameters in this study responded positively to treatments, with statistically significant differences ($P < 0.05$) observed across agronomic performance indicators for the wheat crop. Among the treatment groups, group A (synthetic fertilizer with animal manure) demonstrated the best performance compared to others. This supports findings from studies indicating that high crop yields and enhanced nitrogen use efficiency (NUE) often result in lower N loss through gaseous emissions, as demonstrated in irrigated maize systems in the USA through optimized management of water and N inputs [11]. These findings align with additional studies [43], which reported that increased N application positively affects wheat yield and its components.

The seasonal average outputs of N exhibited significant differences attributable to cropping-specific management systems. Managed treatments demonstrated higher seasonal N removal compared to conventional farming practices. Surprisingly, treatment C_2 recorded the lowest yield at 147.4 kg N ha^{-1}, which may be explained by reduced nitrogen emissions due to the deep placement of nitrogen sources, in contrast to the surface application method commonly employed by farmers.

The positive nitrogen balance of 162 kg N ha^{-1} observed in the managed treatment provides crucial insights into the nitrogen budget within this farming system, indicating opportunities for improvement. These findings align with studies in West African cities. For example, Diogo *et al* [44] reported a significant nitrogen surplus of 126 kg N ha^{-1} due to wastewater irrigation in Niamey, Niger. In contrast, Khai *et al* [36] documented nitrogen inputs ranging from 85 to 882 kg N ha^{-1} in vegetable gardens, Hanoi, Vietnam.

The nitrogen surpluses observed in this study exceed the nitrogen deficits reported by Safi *et al* [35] (−75 kg N ha^{-1}), but remain lower than the extreme surpluses of 882 kg N ha^{-1} recorded by Khai *et al* [36]. The substantial nitrogen accumulations likely stem from the combined contributions of animal manure, night soil, nitrogen in irrigation water, aerosol dust, and condensed sewage water. Conversely, the negative nitrogen balances recorded in some treatments (e.g., B_2 with −5.52 kg N ha^{-1}) indicate nitrogen deficits, though these are considerably lower than the negative balances reported by Safi *et al* [35].

Compared to broader agricultural systems, our findings fall with the range of nitrogen surpluses and deficits reported globally. Watson *et al* [45] documented and an average nitrogen surplus of 83 kg N ha^{-1} yr^{-1} in organic farming systems, whereas Buerkert *et al* [46] measured 131 kg N ha^{-1} in intensively irrigated subtropical farming systems in Oman. These comparisons suggest that nitrogen balances in our study area are relatively high but not unprecedented.

Partial nutrient balances serve as valuable indicators of the sustainability of agricultural systems in Kabul [47]. These balances have been instrumental in enhancing natural resource management and informing policy recommendations over the past two decades [48]. However, it is important to interpret the results cautiously, as this approach has several methodological limitations [49, 50].

Nitrogen efficiencies across treatments, including typical farmer practices and managed systems utilizing animal manure (AM), night soil (NS), urea, diammonium phosphate (DAP), irrigation water, and aerosol dust, ranged from 48% to 130%. The managed treatments featuring deep placement of nitrogen inputs surpassed conventional methods in NUE, with C_2 exhibiting the highest efficiency at 130%, followed by B_1 (102%) and A_3 (99%).

In addition, the analysis of Partial Factor Productivity (PFP) demonstrated that reducing nitrogen inputs resulted in increased PFP, compared to conventional fertilizer management practices. This improvement in PFP with lower nitrogen inputs aligns with findings from Irmack *et al* [51] and Chen *et al* [52].

The soil's chemical properties, including pH, electrical conductivity (EC), bulk density (BD), total nitrogen, phosphorus (P), potassium (K), and organic matter in the surface soil (0.0–0.15 m) remained relatively stable over time, with minimal changes observed in the subsurface soil (0.15–0.30 m). This stability can likely be attributed to the silt loam nature of the soil, which may have facilitated leaching and reduced surface runoff, allowing small particles to be channeled into subsurface pore spaces. In comparison to the findings reported by Safi *et al* [35], this stability suggests minimal declines in pH, EC, and BD, with increases in total nitrogen, plant-available phosphorus, potassium, and organic matter over time.

However, a decline in pH due to prolonged intensive vegetable production has been documented by Wang *et al* [38] and Eneje *et al* [53], who explored the effects of various fertilizer and manure application rates on soil chemistry. If such trends are adequately monitored, a liming program could be considered to maintain soil pH within acceptable limits.

5. Enhancing nitrogen use efficiency and sustainable practices in Kabul's Wheat Farming

The findings of this study highlight critical strategies for improving nitrogen use efficiency (NUE) and minimizing nitrogen losses in Kabul's wheat production system. The enhanced NUE observed in managed treatments suggests that optimizing nitrogen application techniques, particularly through deep placement and balanced organic–inorganic fertilization, could be highly effective in maintaining high crop productivity while reducing nitrogen losses. These strategies would help mitigate environmental impacts and sustain wheat yields. Using green ammonia-based fertilizers alongside traditional fertilizers can also optimize nitrogen use while reducing ammonia emissions, as supported by global research [54].

Subsurface fertilizer application and controlled irrigation scheduling, essential strategies in the study, could be particularly effective in minimizing nitrate leaching and ammonia emissions in Kabul's wheat fields. Precision irrigation systems utilizing IoT-based technologies can help control water and nutrient delivery to the root zone, reducing nitrogen losses, improving water use efficiency, and protecting groundwater quality in Kabul's arid climate [55, 56]. These methods would be critical in addressing the challenges posed by the region's sandy loam soils and irregular rainfall patterns. Additionally, the substantial contributions of organic amendments, such as animal manure and night soil, as found in the study, could be integrated into conventional fertilization systems to improve soil fertility and enhance nitrogen retention. While organic amendments can offer significant nitrogen inputs, it is crucial to establish proper handling and application protocols to avoid potential environmental risks, particularly to water sources [57].

The findings also emphasize the importance of a balanced nutrient management approach that considers not only nitrogen but also phosphorus and potassium, which are crucial for optimizing wheat growth and NUE [58]. By combining organic and inorganic fertilizers, farmers can optimize the availability of these nutrients, improving wheat yields and soil health. Given the variability in nitrogen balances across treatments, targeted educational programs for farmers are needed to promote efficient fertilizer application techniques, regular soil testing, and understanding the crop-specific nutrient needs for wheat. By improving these practices, farmers can reduce excessive fertilizer use, enhance nitrogen sustainability, and increase wheat productivity while safeguarding the environment. In the long term, regular soil and water quality monitoring will be essential to track the effectiveness of these strategies. Further research should explore how nitrogen management, coupled with carbon sequestration practices, can enhance climate resilience and contribute to more sustainable agricultural systems in Kabul's wheat production. This research could also identify the broader implications for other agro-ecosystems in similar arid and semi-arid regions. By integrating these strategies, Kabul's wheat production system can achieve higher nitrogen efficiency, reduce nitrogen losses, and contribute to more sustainable farming practices while sustaining high yields.

5.1. Implications

This study not only contributes to improving nitrogen management in Kabul's wheat production but also highlights significant environmental implications, particularly in addressing the harmful effects of excessive nitrogen losses. Inefficient nitrogen use contributes to air pollution, climate change, and groundwater contamination, exacerbating existing environmental risks. By implementing sustainable nitrogen management practices, including optimized fertilizer application, integrated use of organic amendments, and controlled irrigation techniques, it is possible to reduce nitrogen emissions and leaching, thus mitigating adverse environmental impacts. Moreover, these practices could be instrumental in safeguarding water quality and enhancing soil health, ensuring long-term agricultural productivity in Kabul and other similar regions. The findings underline the urgent need for tailored nutrient management strategies that not only boost crop yields but also protect and preserve the environment for future generations.

6. Conclusions

This study highlights the nitrogen dynamics in a peri-urban wheat-based system in Kabul, emphasizing the impact of local management practices on N distribution, use efficiency, and losses.

(a) Nitrogen distribution and budget

Conventional farmer practices involved high N inputs from (NS), animal manure (AM), urea, and diammonium phosphate (DAP).

All treatment received uniform N inputs from irrigation water (133 kg N ha^{-1} $season^{-1}$) and atmospheric dust (5 kg N ha^{-1}), which significantly contributed to the overall N budget. Although their relative contribution was relatively small compared to fertilizer N inputs. Seasonal N balance indicated positive values in most treatments, except for NS and urea treatments, where losses exceeded uptake.

(b) Efficiency of local management practices

Conventional surface application (A_3) had the highest ammonia (NH_3) emissions, with 55% N losses.

Managed treatments (A_2) and control treatment exhibited lower emissions (32% and 13%, respectively).

Partial Factor Productivity (PFP) improved when N inputs were reduced, demonstrating the potential for optimizing conventional practices.

(c) Magnitude and timing of N losses

Nitrate (NO_3^--N) leaching across treatments reached 385.15 kg ha^{-1} $season^{-1}$, with ammonium (NH_4^+-N) leaching peaking at 68 kg ha^{-1} $season^{-1}$ in surface-applied organic plus chemical fertilizer treatments.

The highest leaching rates were recorded in B and C treatments, likely due to the solubility and release rates of applied N sources.

A positive N balance was observed in most treatments, demonstrating that more N was added to the system than was taken up by crops. However, the night soil and urea treatments and the control showed negative balances, signifying that N losses exceeded crop uptake.

(d) Partial Factor Productivity (PFP) could be improved in conventional management practices by reducing N inputs, reflecting the high background quantities of N present at the site.

(e) Sustainable N Management Strategies

The study underscores the importance of optimized fertilizer placement, reduced surface applications, and improved N synchronization to enhance NUE and minimize environmental losses.

Findings suggest that refining local fertilization practices can reduce excessive N accumulation, improve crop uptake, and mitigate groundwater contamination risks.

The results demonstrate that while current farming practices in Kabul lead to excessive N input and losses, improved nutrient management strategies—such as deep placement and reduced application rates—can enhance NUE, lower emissions, and support long-term agricultural sustainability. Further research is recommended to assess long-term soil health impacts and refine site-specific management strategies.

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Conflict of interest statement

The authors declare no conflict of interest.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.15050795.[59]

Data access statement

The data supporting the findings of this study are available in the Zenodo repository, accessible through the DOI 10.5281/zenodo.15050795.

Ethics statement

This study did not involve human or animal subjects and therefore did not require ethical approval.

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