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Synergistic Effects of Urea, Poultry Manure, and Zeolite on Wheat Growth and Yield

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Abstract: The agricultural sector faces the dual challenge of enhancing crop productivity and mitigating environmental impacts. Optimizing nutrient management is vital for sustainable agriculture, particularly in sloping terrains like the Himalayan region, where damaged soils require restoration. This study explores the synergistic effects of urea, poultry manure, and zeolite on wheat growth and yield in degraded mountainous soils. A total of twelve treatments were implemented in a randomized complete block design, replicated three times. The treatments included a control (T1); urea nitrogen at 120 kg N ha^{-1} (UN_{120}) (T2); poultry manure (PM) at 120 kg N ha^{-1} (T3); zeolite-1 (Z1) at 5 t ha^{-1} (T4); zeolite-2 (Z2) at 5 t ha^{-1} (T5); UN_{120} + Z1 (T6); PM + Z1 (T7); UN_{120} + Z2 (T8); PM + Z2 (T9); ½ UN + ½ PM + Z1 (T10); ½ UN + ½ PM + Z2 (T11); and ½ UN + ½ PM + ½ Z1 + ½ Z2 (T12). The UN_{120} treatment demonstrated significant improvements in wheat growth, with notable increases in shoot length (79.7%), shoot fresh weight (50.8%), root length (50.6%), chlorophyll content (53.6%), and leaf area (72.5%) compared to the control. Wheat yield and its components experienced significant improvements when treated with urea nitrogen (UN) and zeolites. Among these treatments, UN_{120} exhibited the highest efficacy. Nutrient content analysis revealed substantial increases in shoot nitrogen (70.6%), phosphorus (33.3%), and potassium (15.6%) with UN_{120} treatment compared to the control. The concoction of UN and PM with zeolites further enhanced nutrient levels. Integrating mineral nitrogen sources with organic amendments and zeolites proved effective in enhancing wheat productivity in degraded mountainous soils. Despite positive results, further research is essential for widespread recommendations.

Keywords: urea; poultry manure; zeolite; wheat; nutrient uptake; yield

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1. Introduction

Nitrogen (N) plays a crucial role as an essential nutrient that influences both plant growth and physiological functions [1]. It facilitates rapid vegetative growth, enhances glucose digestion, and influences seed quality by elevating protein levels while reducing oil content [2]. Additionally, nitrogen constitutes a fundamental component of chlorophyll, the dark green pigment imparting color to leaves, capturing light energy for photosynthesis, and promoting increased photosynthetic activity [3]. Nitrogen fertilizer application proves particularly beneficial in enhancing crop output and quality, especially in cereals, ensuring optimal economic benefits [4].

The exogenous supply of nitrogen through chemical fertilizers is crucial for the long-term viability of agricultural ecosystems, especially in intensive production systems where natural nitrogen sources fall short of meeting crop requirements [5]. However, the prolonged and recurrent use of chemical fertilizers, exceeding plant needs, lead to issues such as soil acidity, harm to beneficial microbial biota, nutrient deficiencies, and overall degradation of the soil and environment [6]. Moreover, the improper utilization of fertilizers on sloping soils, through processes like surface run-off, leaching, denitrification, and volatilization, results in significant losses, contributing to pollution and reduced fertilizer efficiency [7].

Factors such as the shortage and low availability of chemical fertilizers at the correct time, escalating prices, adulteration, and the elimination of government subsidies further deter farmers from using mineral N fertilizers in prescribed amounts. On the other hand, organic amendments, including animal manures like farm yard manure (FYM), poultry manure (PM), pigeon manure, crop residues, and various industrial and municipal wastes, are commonly reintegrated into cultivated soils to enhance crop yields and soil quality [8–12].

Organic manures, such as poultry manure (PM), contribute to plant growth by improving the physical, chemical, and biological qualities of the soil. They ensure balanced nutrient delivery, and generate long-lasting residual effects on soil nutrient availability [13]. Despite their potential benefits, challenges such as low nutrient content, slow nutrient release, and handling difficulties make the application of organic manure to crops challenging in organic farming systems [14]. Additionally, the excessive use of PM can also lead to the eutrophication of ponds and water reservoirs, compromising their quality [15].

Zeolites are widely used minerals known for their exceptional ion exchange capacity [16]. They play a crucial role in agriculture by capturing, storing, and slowly releasing nitrogen, thereby enhancing nutrient availability in contaminated soil [17,18]. Zeolites also exhibit high affinity for heavy metals [19], making them effective in water treatment [20]. The primary application of zeolites in agriculture is for the capture, storage, and slow release of nitrogen. When combined with nitrogen, phosphorus, and potassium compounds, zeolite enhances the efficacy of these compounds as slow-release fertilizers [21]. It has been reported that zeolites can enhance the efficiency of organic fertilizers, especially composts, by positively influencing soil physicochemical properties, soil acidity, salinity, and plant growth [16]. Soudejani et al. [22] highlighted that incorporating zeolite with manure enhances the effectiveness of organic fertilizers. Additionally, Cairo et al. [23] reported that the application of zeolite with organic fertilizers not only improves soil quality but also enhances the yield of sugarcane. However, relying solely on organic manures or zeolites may not meet all of a plant's immediate nutrient requirements, due to their low nutrient content and gradual availability. While mineral fertilizers offer nutrients in easily accessible and concentrated forms, they lack in sustaining long-term crop production and contribute nothing to the build-up of organic matter.

To address these challenges, intelligently integrating available organic and inorganic nutrient sources is essential for sustaining soil health, maintaining environmental quality, and ensuring long-term crop yields. Integrated Plant Nutrient Management (IPNM) emerges as an ecologically comprehensive and environmentally friendly approach that enables plants to meet their nutritional needs on a long-term basis through a combination of chemical fertilizers and organic amendments [9,24,25].

The combination of organic additions with reduced levels of chemical fertilizers has the potential to improve crop yields, nitrogen use efficiency (NUE), and the nutrient-providing capability of degraded soils while reducing the risk of contamination [26]. Ramesh et al. [27] evaluated the impact of various organic manures—cattle dung manure (CDM), poultry manure (PM), and vermicompost (VC)—and inorganic fertilizers on soybean-drum wheat soil quality and production. They reported significant gains in soil organic carbon (SOC), soil nutrient levels, and grain yields compared to mineral fertilizers. Bhattacharyya et al. [28] observed substantial increases in organic carbon (OC), total nitrogen (TN), available phosphorus (AP), and available potassium (AK) in soils supplemented with NPK fertilizers + FYM compared to NPK-fertilized soils in a soybean–wheat cropping system in the Indian Himalayas. Additional research studies [9,29] further indicate that IPNM not only improves soil physical conditions but also exhibits synergistic effects on nutrient release and uptake by crops, contributing to improved water and nutrient utilization from the soil.

The current study hypothesizes that the integration of organic and inorganic nutrient sources through IPNM would positively influence wheat growth, yield, and nutrient uptake, concurrently enhancing short-term soil organic matter, nitrogen, and phosphorus levels. Considering the significance of wheat in the country's economy and the potential contribution of IPNM in preserving yield and soil health, this study aims to address the following objectives: (i) examine the impact of various organic and inorganic additives on wheat growth, yield, and nutrient uptake, and (ii) analyze the short-term changes in soil organic matter, nitrogen, and phosphorus after applying organic–inorganic amendments or a mix of them.

2. Materials and Methods

2.1. Plant Material

Wheat (*Triticum aestivum* L.) cv. "Sagar" was used as a test crop in this study. Healthy and mature seeds, which had a 95% germination capacity, were obtained from National Agriculture Research Centre (NARC), Islamabad, Pakistan. This is a local variety and is recommended for both rainfed and irrigated field conditions.

2.2. Site Description

In the winter of 2020–2021, a field experiment was conducted at the University of Poonch Rawalakot's experimental farm in northeastern Pakistan, located beneath the foothills of the great Himalayas at coordinates 33.51° N and 73.45° S, with an altitude of 1676 m (Figure 1). The region's topography is characterized by hilly and mountainous terrain, including valleys and plains. It experiences a temperate sub-humid climate with annual rainfall ranging from 500 to 2000 mm, occurring irregularly with intense storms during the monsoon and winter. The mean annual temperature is around 301.15 K in summer, and winters are notably cold, with temperatures occasionally falling below freezing [30,31]. The area faces a moderate risk of water erosion, resulting in significant annual loss of soil, organic matter, and essential plant nutrients. Traditionally, farmers follow a cropping sequence of summer maize followed by winter wheat, with minimal or no application of recommended fertilizers [32].

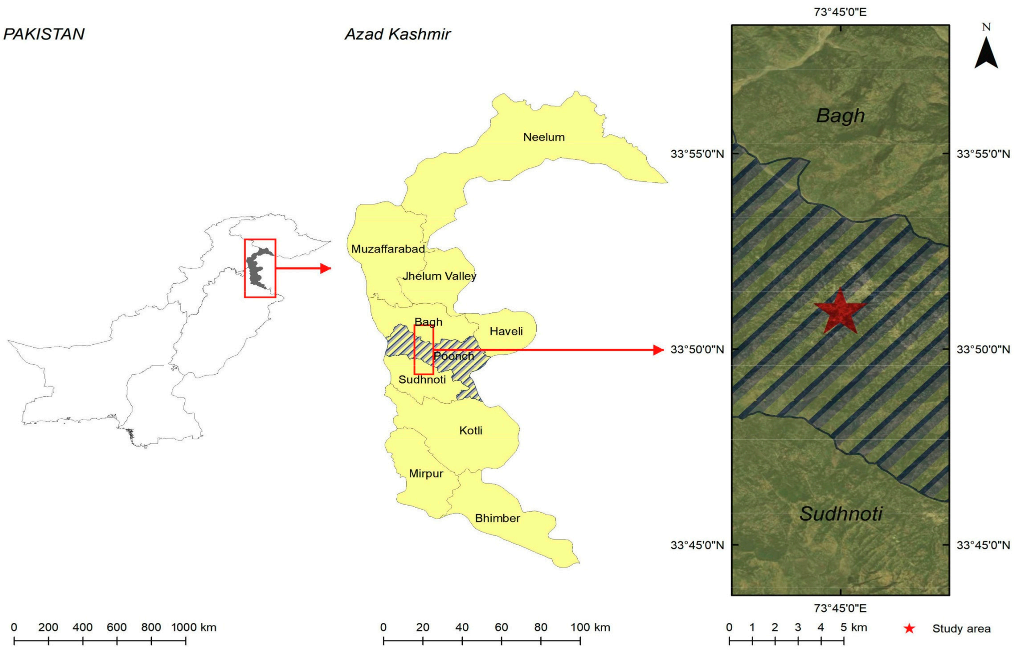

Figure 1. Map showing location of the study area and the experimental site.

2.3. Soil Analysis

Soil samples from the 0–20 cm layer were collected in each plot before the start of the experiment using a soil auger with a 76 mm diameter. From each plot, three representative samples were taken. These samples were air-dried, crushed to pass through a 2 mm sieve, mixed to make a composite sample, labeled, and stored in plastic bags. Standard laboratory methods were used for physical and chemical characterization of the soil. Soil texture was determined using a hydrometer method [33]. Soil acidity (pH) and electrical conductivity (EC) were determined in soil and water suspension of 1:5 [34], and soil organic matter content (SOM) was determined by using $K_2Cr_2O_7$ as an oxidizing agent as described by Nelson and Sommers [35]. The ammonium bicarbonate-diethylenetriaminepentaacetic acid (AB-DTPA) extractable P and K were analyzed using the method as described by Soltanpour and Schawab [36]. Total nitrogen in soil was determined using Kjeldahl distillation procedure as described by Bremner [37]. The soil type, a Calcaric Luvisols according to the World Reference Base (WRB) system of soil taxonomy, had a sandy-loam texture (60% sand; 25% silt; 15% clay), slightly alkaline in reaction (pH 7.3), low in organic matter content (7.8 g kg^{-1}). Furthermore, the soil registered a low concentration of AB-DTPA extractable phosphorous of 6.5 mg kg^{-1}, a total N of 0.4 g kg^{-1}, and exchangeable potassium (AB-DTPA) of 82 mg kg^{-1}. Additionally, post-harvest soil samples were also collected to evaluate the treatment effects on total nitrogen, phosphorus, potassium, organic matter, and soil pH.

2.4. Experimental Inputs

Two types of synthetic zeolites were purchased from a scientific store in Islamabad, Pakistan. Zeolite (Z1) was a hydrated aluminosilicate zeolite containing silicon, aluminum, oxygen, and tin, while zeolite (Z2) was a hydrated sodium zeolite containing silicon, aluminum, oxygen, and sodium. Poultry manure (PM) was purchased from a local poultry farm. PM was composed of 1.4% N, 0.82% P, and 0.7% K. The chemical fertilizer utilized in this study was urea ($CO(NH_2)_2$) (46% N).

2.5. Details of Experimental Design and Treatments

This study aimed to investigate the integrated impact of urea, poultry manure, and zeolite on wheat growth and yield. The treatments included mineral nitrogen as urea (UN), poultry manure (PM), Synthetic zeolites, and a control group with no amendments. These amendments were applied either individually or in various combinations. In total, 12 treatments were employed in this study: control (T_1); urea nitrogen (UN) at 120 kg N ha^{-1} (T_2); poultry manure (PM) at 120 kg N ha^{-1} (T_3); zeolite-1 (Z_1) at 5 t ha^{-1} (T_4); zeolite-2 (Z_2) at 5 t ha^{-1} (T_5); UN + Z_1 (T_6); PM + Z_1 (T_7); UN + Z_2 (T_8); PM + Z_2 (T_9); ½ UN + ½ PM + Z_1 (T_{10}); ½ UN + ½ PM + Z_2 (T_{11}); ½ UN + ½ PM + ½ Z_1 + ½ Z_2 (T_{12}). All treatments were randomly assigned to respective plots before crop sowing using a randomized complete block design (RCBD) with three replications. The plot size was 3 × 3 m with 10 rows, and the row-to-row distance was maintained at 30 cm. Prior to the experiment, the field underwent two ploughing sessions with a cultivator, followed by a rotavator for seed bed preparation. The wheat cultivar "Sagar" was sown on 28 November 2020, by uniformly drilling at a depth of 3 cm into rows spaced 30 cm apart, at the recommended rate of 120 kg ha^{-1}. Standard local cultural practices were adhered to throughout the growth period, including manual weeding as needed. No irrigation was provided, and wheat was harvested manually at physiological maturity 167 days after sowing on 15 May 2021.

2.6. Data Collection

2.6.1. Growth Parameters

The collected data encompassed various growth parameters, like shoot length, shoot fresh weight, root length, root fresh weight, shoot dry weight, and spike length. Root length (RL), spike length, and shoot length (SL) were measured in cm using a ruler. The shoot fresh weight (SFW), root fresh weight (RFW), and shoot dry weight (SDW) were measured using an electric weight balance, and these traits were recorded in grams. The measurement procedures for these parameters are consistent with those reported by Ahmed et al. [38]. Plant leaf area was measured by multiplying the leaf length and width of samples (3 middle leaves) of five tillers by a correction factor (CF = 0.65) using the following formula [24].

$$\text{Leaf area}\left(\text{cm}^2\right) = \text{Average of leaf area} \times \text{Number of leaves per plant} \times \text{CF} \quad (1)$$

2.6.2. Yield and Related Trails

Data related to yield and its associated parameters, including the number of grains per spike, 1000-grain weight, grain and biological yield, dry matter yield, and harvest indexes, were comprehensively considered. To determine the number of grains per spike, five spikes were randomly selected, and individual grains were counted. The average count was then calculated. The 1000-grain weight (g) data were measured using an electronic balance by counting a thousand grains randomly selected from each plot. Manual harvesting of the crop was carried out for each plot separately. Harvested plants were bundled and sun-dried until a constant weight was achieved to reduce moisture content. The biological yield was recorded by weighing the sun-dried bundles of each plot with a spring balance (50 kg capacity), and the yield is expressed in kilograms per hectare (kg ha^{-1}). Subsequently, each plot underwent manual threshing using a wheat thresher to record grain yield. The cleaned grains were weighed in kg. For each treatment, grain yield, biological yield, and harvest index were calculated using Equations (2), (3), and (4), respectively [24].

$$\text{Biological yield}\left(\text{kg ha}^{-1}\right) = \frac{\text{Total plant weight in 4 central rows}}{\text{R} - \text{R distance (m)} \times \text{Row length (m)} \times \text{No. of rows}} \times 10 \quad (2)$$

$$\text{Grain yield}\left(\text{kg ha}^{-1}\right) = \frac{\text{Biological yield in 4 central rows}}{\text{R} - \text{R distance (m)} \times \text{ Row length (m)} \times \text{ No. of rows}} \times 10 \quad (3)$$

$$\text{Harvest index (\%)} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100 \quad (4)$$

2.6.3. Biochemical Analysis of Plant and Grain Samples

Wheat plant and grain samples underwent a drying process in an air-forced oven at 65 °C for approximately 48 h. Subsequently, they were ground in a Wiley mill (Polymix PX-MFC 90D; Luzern, Switzerland) to pass through a 1 mm sieve. The estimation of total nitrogen (N) in the ground plant material was conducted using the Kjeldhal digestion method, followed by distillation and titration [39]. Total phosphorus (P) and potassium (K) levels were determined by digesting 0.25 g of the material with sulfuric acid and hydrogen peroxide. Phosphorus in the digests was measured via colorimetry, utilizing P standards of potassium dihydrogen phosphate [40], while potassium was determined using an atomic absorption spectrophotometer [41]. The calculation of total nitrogen–phosphorus–potassium (NPK) plant uptake was derived from dry matter (DM) accumulation and NPK concentration in the wheat shoot. Additionally, grain samples of wheat were analyzed for nitrogen, phosphorus, and potassium concentrations using the same procedures as those employed for plant analysis. The NPK uptake in grains was computed by multiplying the concentrations of NPK in the grains by the grain yield, following the methodology outlined by Jamal et al. [9] and Saeed et al. [42]. To measure chlorophyll content, a piece of leaf (1 cm^2) was collected and placed into a test tube, along with 5 mL of acetone. The tube was then placed in the dark overnight [43]. Subsequently, a spectrophotometer was employed to measure the absorbance at 663 nm and 645 nm, corresponding to chlorophyll a and b. The calculation of total chlorophyll content was carried out as follows:

$$\text{Total Chlorophyll } = 8.02 \times (\text{A 663 nm}) + 20.2 \times (\text{A 645 nm})$$

2.7. Statistical Analysis

Data obtained were subjected to statistical analysis using Statistix 8.1 (Statistix 8.1, Tallahassee, FL, USA). One-way ANOVA for randomized complete block design (RCBD) and multiple comparison analyses using Tukey's test at $p < 0.05$ were performed and the means were separated using least significant difference ($LSD_{0.05}$) test [44].

3. Results

3.1. Impact of Various Treatments on Wheat Growth Characteristics

The study results indicated that the application of UN alone or with PM and zeolites significantly ($p \leq 0.05$) increased most growth characteristics compared to the control (Table 1). Growth characteristics like shoot length, shoot fresh weight, shoot dry weight chlorophyll contents, and leaf area increased when solo nitrogen (UN_{120}) was used. Urea alone did not reach a significant level compared to the combined application of urea + PM + zeolites. Notably, the UN_{120} treatment exhibited remarkable enhancements, resulting in substantial increases in shoot length (79.7%), shoot fresh weight (50.8%), shoot dry weight (114.3%), root length (50.6%), root fresh weight (37.0%), chlorophyll content (53.6%, Figure 2), and leaf area (72.5%, Figure 3), compared to the control group. PM_{120} also demonstrated noteworthy effects, resulting in a notable increase in shoot length (19.6%), shoot dry weight (89.3%), and root length (51.9%).

Table 1. Effect of UN, PM, and zeolite on growth characteristics of wheat (*Triticum aestivum* L.).

Treatments	Shoot Length (cm)	Shoot Fresh Weight (g)	Shoot Dry Weight (g)	Root Length (cm)	Root Fresh Weight (g)
Control	39.1 e	5.9 e	2.8 f	7.7 b	2.7 f
UN_{120}	70.3 a	8.9 a	6.0 a	11.6 a	3.7 a–e
PM_{120}	46.8 de	7.8 abc	5.3 abc	11.7 a	3.5 cde
Z_1	40.4 e	6.2 de	4.2 e	8.3 b	3.1 def
Z_2	40.1 e	6.4 de	4.3 de	8.0 b	3.1 def
$UN_{120} + Z_1$	69.5 a	7.7 bc	5.2 a–d	12.4 a	3.7 bcde
$PM_{120} + Z_1$	58.9 bc	7.1 cd	4.8 b–e	12.2 a	3.8 abc
$UN_{120} + Z_2$	67.7 a	7.8 abc	5.3 abc	12.4 a	3.8 abcd
$PM_{120} + Z_2$	54.4 cd	6.6 de	4.4 cde	11.3 a	3.7 bcde
$UN_{60} + PM_{60} + Z_1$	67.0 ab	8.4 ab	5.7 ab	12.9 a	4.4 a
$UN_{60} + PM_{60} + Z_2$	65.6 ab	8.5 ab	5.7 ab	12.0 a	4.2 ab
$UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2$	65.7 ab	8.3 ab	5.7 ab	11.2 a	4.2 ab
LSD ($p \leq 0.05$)	8.34	1.10	0.94	2.06	0.68

Means sharing the same letters in the column do not differ significantly at 5% probability. UN = urea nitrogen; PM = poultry manure; Z_1 and Z_2 = zeolites.

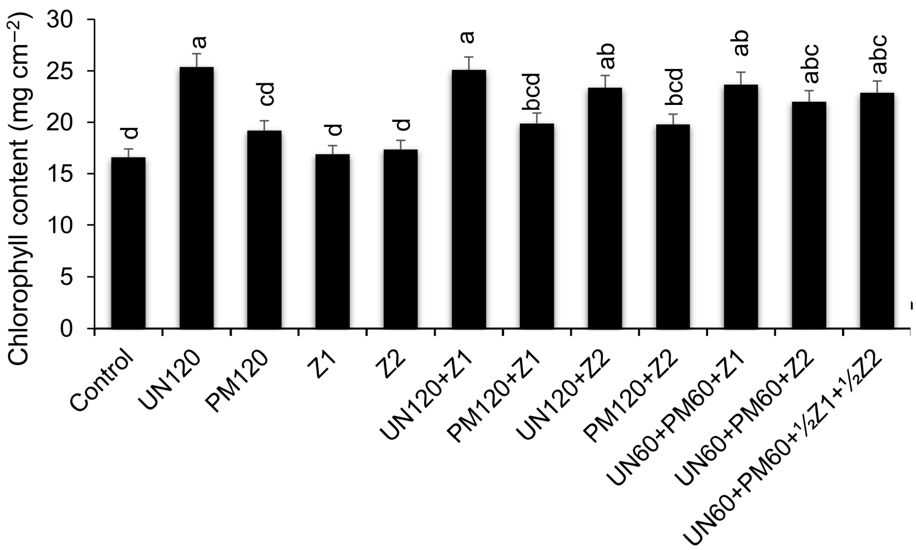

Figure 2. Effect of UN, PM, and zeolite on chlorophyll content of wheat (*Triticum aestivum* L.). Means sharing the same letters in the column do not differ significantly at 5% probability. UN = urea nitrogen; PM = poultry manure; Z1 and Z2 = zeolites.

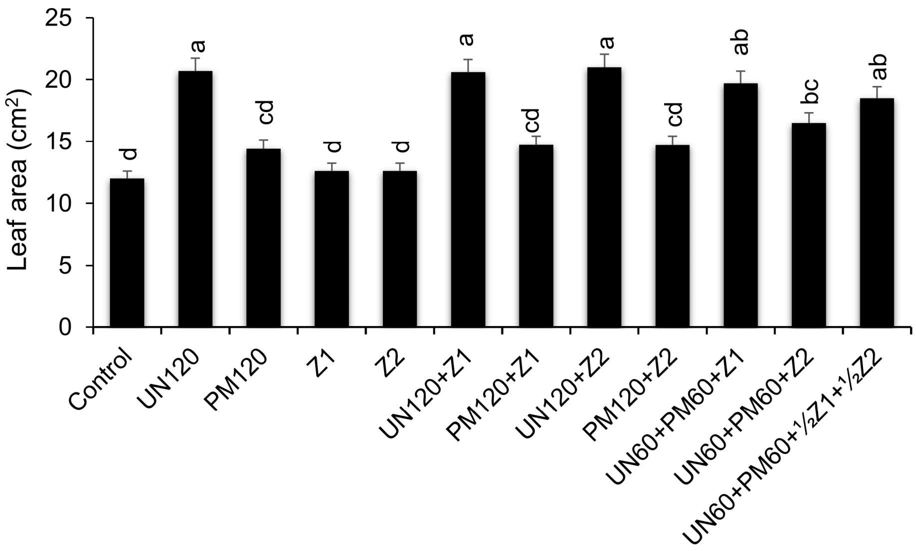

Figure 3. Effect of UN, PM, and zeolite on leaf area of wheat (*Triticum aestivum* L.). Means sharing the same letters in the column do not differ significantly at 5% probability. UN = urea nitrogen; PM = poultry manure; Z1 and Z2 = zeolites.

3.2. Effect of Different Soil Amendments on Yield and Yield Attributes of Wheat

The yield and yield components of wheat grown on the soil amended with UN and zeolites were significantly ($p \leq 0.05$) higher compared to the control (Table 2). The UN_{120} treatment demonstrated significant improvements, resulting in a substantial increase in the number of grains per spike (74.9%), spike length (92.5%), 1000-grain weight (20.0%), straw yield (41.2%), grain yield (78.1%), and biological yield (51.4%) compared to the control group. PM_{120} also showed notable effects, with increased spike length (45.3%) and grain yield (18.5%). Zeolite treatments (Z_1 and Z_2) demonstrated positive effects on agronomic parameters. Z_1 resulted in a 5.5% increase, and Z_2 showed a 3.8% increase in grain yield compared to the control. Both zeolites also contributed to improvements in spike length and 1000-grain weight. The combinations of UN and PM with zeolites, specifically $UN_{120} + Z_1$, $PM_{120} + Z_1$, $UN_{120} + Z_2$, and $PM_{120} + Z_2$, exhibited synergistic effects on the agronomic parameters of wheat (Table 2).

Table 2. Effect of UN, PM, and zeolite on yield and yield attributes of wheat (*Triticum aestivum* L.).

Treatments	No. of Grains Spike^{-1}	Spike Length (cm)	1000-Grain Weight (g)	Straw Yield (kg ha^{-1})	Grain Yield (kg ha^{-1})	Biological Yield (kg ha^{-1})	Harvest Index (%)
Control	19.9 e	5.3 e	27.5 e	2979 e	1060 d	4040 d	26.2
UN_{120}	34.7 a	10.2 ab	33.3 ab	4201 a	1888 a	6122 a	31.0
PM_{120}	25.8 cde	7.7 cd	28.2 cde	3542 c–e	1258 cd	4800 bc	26.2
Z_1	20.3 e	8.4 c	28.1 cde	3098 de	1103 cd	4202 cd	26.3
Z_2	20.3 e	7.0 d	27.9 de	3023 e	1097 cd	4120 d	26.6
$UN_{120} + Z_1$	33.0 ab	10.5 a	35.5 a	4254 a	1823 a	6077 a	30.0
$PM_{120} + Z_1$	26.1 b–e	9.8 ab	29.6 b–e	3616 bc	1303 c	4919 b	26.5
$UN_{120} + Z_2$	31.5 a–d	10.3 ab	32.3 a–d	4214 a	1908 a	6089 a	31.2
$PM_{120} + Z_2$	24.6 de	9.0 bc	29.9 b–e	3602 b–d	1295 cd	4897 b	26.4
$UN_{60} + PM_{60} + Z_1$	31.9 a–c	10.1 ab	33.0 ab	3916 a–c	1780 ab	5696 a	31.3
$UN_{60} + PM_{60} + Z_2$	28.2 a–d	9.9 ab	32.6 abc	4078 ab	1547 b	5625 a	27.5
$UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2$	32.6 a–c	10.2 ab	32.4 a–d	4169 a	1698 ab	5866 a	28.9
LSD ($p \leq 0.05$)	6.90	1.37	4.65	538.0	237.7	535.6	NS

Means sharing the same letters in the column do not differ significantly at 5% probability. UN = urea nitrogen; PM = poultry manure; Z_1 and Z_2 = zeolites.

3.3. Effect of Different Soil Amendments on Nutrient Content of Shoot and Grain of Wheat

The analysis of nutrient content in wheat shoots and grains under different treatments showed significant variations (Table 3). The UN_{120} treatment exhibited notable increases in shoot nitrogen (70.6%), shoot phosphorus (33.3%), and shoot potassium (15.6%), as well as elevated grain nitrogen (37.7%) and grain potassium (22.4%) compared to the control. Similarly, the PM_{120} treatment resulted in enhanced shoot nitrogen (24.5%), shoot phosphorus (50.0%), shoot potassium (6.7%), grain nitrogen (20.8%), and grain potassium (34.5%). The combinations of UN and PM with zeolites (Z1 and Z2) further augmented nutrient levels, with the UN_{120} + Z1 treatment showing the highest values for shoot nitrogen and grain potassium (Table 3).

Table 3. Effect of UN, PM, and zeolite on nutrient content of shoot and grain contents of wheat (*Triticum aestivum* L.).

Treatments	Shoot Nitrogen (g kg^{-1})	Shoot Phosphorous (g kg^{-1})	Shoot Potassium (g kg^{-1})	Grain N (g kg $^{-1}$)	Grain P (g kg^{-1})	Grain K (g kg^{-1})
Control	9.41 d	1.2 f	9.0 f	15.4 e	4.9 d	5.8
UN_{120}	16.08 ab	1.6 e	10.4 e	21.2 abc	5.3 cd	6.0
PM_{120}	11.7 bcd	1.8 abcd	11.4 de	18.5 d	6.9 ab	7.1
Z_1	9.4 d	1.2 f	11.9 cd	15.5 e	5.0 d	7.6
Z_2	9.3 d	1.2 f	12.1 bcd	15.0 e	4.9 d	7.4
UN_{120} + Z_1	16.6 a	1.6 de	13.0 abc	21.8 a	5.3 cd	7.2
PM_{120} + Z_1	11.7 bcd	1.9 a	12.8 abc	18.8 bcd	7.1 a	7.7
UN_{120} + Z_2	16.3 a	1.7 cde	13.0 abc	21.5 ab	5.5 cd	7.1
PM_{120} + Z_2	11.5 cd	1.9 ab	12.7 abc	18.6 cd	7.0 a	7.8
UN_{60} + PM_{60} + Z_1	15.9 abc	1.8 abc	13.1 ab	22.4 a	6.1 abc	6.6
UN_{60} + PM_{60} + Z_2	15.8 abc	1.7 bcde	13.0 abc	20.7 a–d	6.3 abc	6.5
UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2	15.4 abc	1.7 cde	13.2 a	21.5 ab	5.9 bcd	7.2
LSD ($p \leq 0.05$)	4.54	0.182	1.145	2.833	1.084	NS

Means sharing the same letters in the column do not differ significantly at 5% probability. UN = urea nitrogen; PM = poultry manure; Z_1 and Z_2 = zeolites.

3.4. Effect of Different Soil Amendments on Shoot and Grain Nutrient Uptake of Wheat

The application of different amendments (UN, PM, zeolites, or their combinations) significantly ($p \leq 0.05$) affected shoot and grain nitrogen, phosphorus, and potassium uptake in wheat (Table 4). The minimum shoot N-uptake (13.5 kg ha^{-1}) was recorded for the control treatment. The shoot N-uptake in Z_1 and Z_2 treatments was on par with the control. The differences among all the treatments (except for zeolites) were non-significant. However, the combination of UN, PM, and zeolites in UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2 treatments increased shoot N-uptake by 94.8, 106.6, and 112.6%, respectively, compared to the control. The highest shoot N-uptake was recorded for the combined treatment (UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2).

The shoot P-uptake varied between 3.4 and 7.1 kg ha^{-1} among the amendments, exhibiting a relative increase of 7.5 to 125% over the control. The zeolites receiving treatments were not able to bring a significant increase in shoot P-uptake, and values were on par with the control. The application of UN, PM, and zeolites in combined treatments, i.e., UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2, recorded 125.0, 91.8, and 87.5% increases in shoot P-uptake relative to the control treatment, respectively. The highest shoot P-uptake was recorded for UN_{60} + PM_{60} + Z_1 treatment (Table 4).

Table 4. Effect of UN, PM, and zeolite on shoot and grain N, P, K uptake of wheat (*Triticum aestivum* L.).

Treatments	Shoot N-Uptake (kg ha^{-1})	Shoot P-Uptake (kg ha^{-1})	Shoot K-Uptake (kg ha^{-1})	Grain N-Uptake (kg ha^{-1})	Grain P-Uptake (kg ha^{-1})	Grain K-Uptake (kg ha^{-1})
Control	13.5 b	3.1 c	27.0 d	16.3 d	5.2 b	6.1 e
UN_{120}	24.9 a	5.4 abc	41.3 bc	40.0 a	10.1 a	11.3 abc
PM_{120}	25.6 a	6.2 a	41.6 bc	23.2 cd	8.7 a	8.9 cd
Z_1	16.4 b	3.5 bc	37.5 c	17.1 d	5.5 b	8.4 de
Z_2	16.8 b	3.4 c	37.0 c	16.5 d	5.4 b	8.1 de
UN_{120} + Z_1	28.1 a	6.1 a	50.8 a	39.8 a	9.7 a	13.1 a
PM_{120} + Z_1	27.1 a	7.1 a	45.1 ab	24.5 c	9.2 a	10.0 bcd
UN_{120} + Z_2	27.5 a	6.1 a	50.9 a	41.1 a	10.6 a	13.5 a
PM_{120} + Z_2	25.0 a	6.8 a	44.7 abc	24.1 c	9.1 a	10.1 bcd
UN_{60} + PM_{60} + Z_1	26.3 a	7.1 a	50.3 a	39.9 a	10.9 a	11.8 ab
UN_{60} + PM_{60} + Z_2	27.9 a	6.1 a	51.5 a	32.0 b	9.8 a	10.0 bcd
UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2	28.7 a	5.9 ab	51.8 a	36.5 ab	10.0 a	12.2 ab
LSD ($p \leq 0.05$)	5.298	2.512	7.955	7.052	2.326	2.516

Means sharing the same letters in the column do not differ significantly at 5% probability. UN = urea nitrogen; PM = poultry manure; Z_1 and Z_2 = zeolites.

The relative increase in shoot K-uptake (over the control) varied between 37.0 and 91.8% among different amendments. The shoot K-uptake in response to the sole application of zeolites (Z_1 and Z_2) varied between 37 and 39% compared with the control, respectively. The application of PM with zeolites in PM_{120} + Z_1 and PM_{120} + Z_2 combinations further increased shoot K-uptake by about 20.0% over the sole application of zeolites (Table 4). When half UN was combined with PM + Zeolites in the combined treatments (UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2), the shoot K-uptake increased by 86.3, 90.7, and 91.8%, respectively, over the control treatment. The highest shoot K-uptake was recorded for UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2 treatments.

The grain N-uptake values among the amendments varied between 16.5 and 41.1 kg ha^{-1}, showing a relative increase of 1.2 to 152.1% over the control treatment. The combination of PM with zeolites in PM_{120} + Z_1 and PM_{120} + Z_2 treatments increased grain N-uptake by 43.3 and 46.0% over the sole application of zeolites, respectively. The grain N-uptake in combined treatments (UN_{60} + PM_{60} + Z, UN_{60} + PM_{60} + Z_1, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2) increased by 144.8, 96.3, and 123.9%, respectively, over the control. The combination of UN_{120} + Z_2 recorded the highest grain N-uptake (Table 4).

The grain P-uptake in Z_1 and Z_2 treatments was on par with the control. Non-significant differences were observed for all the treatments (except for zeolites). The combination of amendments in UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2 treatments increased grain P-uptake by 83.6, 88.3, and 91.6%, respectively, compared to the control. The highest grain P-uptake was recorded in UN_{60} + PM_{60} + Z_1 treatment followed by UN_{120} + Z_2 (Table 4).

The grain K-uptake in Z_1 and Z_2 treatments was on par with the control. The application of PM and zeolites in PM_{120} + Z_1 and PM_{120} + Z_2 combinations increased grain K-uptake by 19.0 and 24.7%, respectively, over the Z_1 and Z_2 treatments alone. The differences among all the treatments (except for zeolites) were non-significant. However, the combination of UN, PM, and zeolites in UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2 treatments increased grain K-uptake by 93.4, 63.9, and 100%, respectively, over the control. The highest grain K-uptake was recorded for the treatment UN_{120} + Z_2 followed by UN_{120} + Z_1 and both were on par with each other (Table 4).

3.5. Total N, P, and K Uptake by Wheat

The results revealed that the application of organic–inorganic amendments (except for zeolites) significantly ($p \leq 0.05$) increased total N-uptake between 33.3 and 68.6 kg ha^{-1} compared to the control (29.8 kg ha^{-1}), exhibiting a relative increase of 11.7 to 130.2% over the control (Figure 4A). The treatments Z_1 and Z_2 were on par with the control. However, when PM was combined with zeolites in PM_{120} + Z_1 and PM_{120} + Z_2 treatments, the total N-uptake showed an increase of 53.7 and 47.4% over the sole application of zeolites, respectively. Total N-uptake in the combined N treatments (UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2) was 122.1, 101.1, and 118.8%, respectively, higher than the control. The maximum total N-uptake was recorded in UN_{120} + Z_2 followed by UN_{120} + Z_1 and the difference between the two was non-significant.

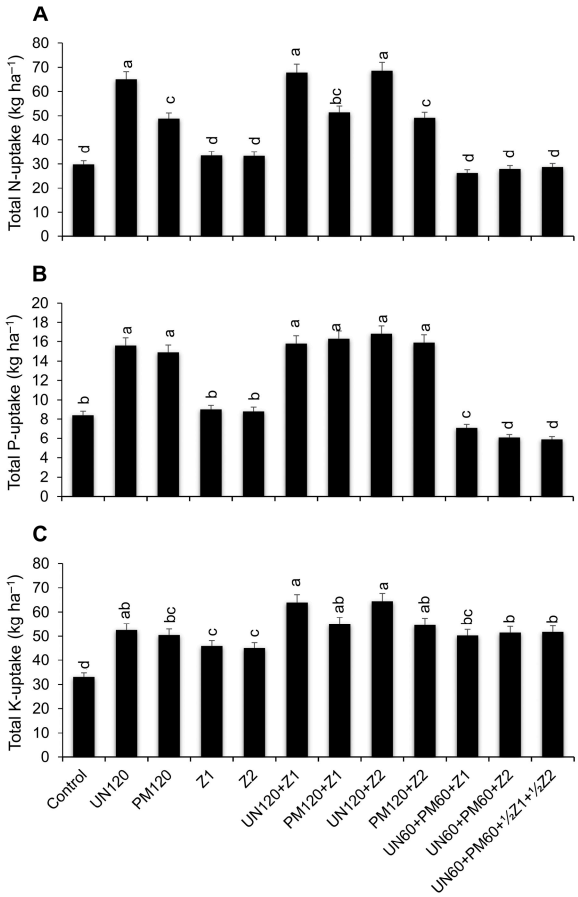

Figure 4. Effect of UN, PM, and zeolite on total N (**A**), total P (**B**), and total K uptake (**C**) of wheat (*Triticum aestivum* L.). Means sharing the same letters in the column do not differ significantly at 5% probability. UN = urea nitrogen; PM = poultry manure; Z_1 and Z_2 = zeolites).

The total P-uptake for the amended soil varied between 8.8 and 18.1 kg ha^{-1}, exhibiting a relative increase of 5.5 to 115.6% over the control. The control treatment recorded the lowest total P-uptake of 8.4 kg ha^{-1} and the values recorded for the zeolite treatments were on par with the control (Figure 4B). The combination of UN, PM, and zeolites in UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2 treatments increased total P-uptake by 115.6, 89.5, and 90.0%, respectively, compared to the control. The combination of amendments in UN_{60} + PM_{60} + Z_1 recorded the highest total P-uptake (Figure 4B).

The relative increase in total K-uptake (over the control) for Z_1 and Z_2 was 38.7 and 36.2%, respectively. The combined application of PM_{120} + Z_1 and PM_{120} + Z_2 further increased total K-uptake by 20.0 and 21.3%, respectively, over Z_1 and Z_2 alone. When half UN was applied with PM + zeolites in UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} +

PM_{60} + ½ Z_1 + ½ Z_2 combinations, the total K-uptake increased between 85.8 and 93.6% over the control. Among different amendments, the combined use of UN_{120} + Z_2 recorded the highest total K-uptake (64.4 kg ha^{-1}) and was equivalent to 64.1 kg ha^{-1} recorded for the UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2 treatment (Figure 4C).

3.6. Post-Harvest Soil pH, Organic Matter, Total N, and AB-DTPA Extractable P and K

The application of UN and PM alone or with zeolites significantly ($p \leq 0.05$) changed soil pH compared to the control. Soil pH varied between 7.0 and 7.5 among the organic-inorganic amendments, with the lowest being in UN_{120} and the highest being in PM_{120} treatments. In the case of UN-amended soil, the pH decreased by 4.3% while the PM-amended soil showed a 3.1% increase in pH compared to the control. The pH recorded for the control soil was 7.3. The application of UN, zeolites, and their combinations did not significantly ($p \leq 0.05$) increase/decrease the soil pH and the values were on par with the control. However, when PM was applied in combination with UN + zeolites in UN_{60} + PM_{60} + Z_1 and UN_{60} + PM_{60} + Z_2 treatments, the pH increased by 1.9 and 2.5%, respectively, compared to the combined application of UN_{120} + Z_1 and UN_{120} + Z_2, and there were non-significant differences between these two treatments (Table S1).

The control treatment had the lowest soil organic matter (SOM) content (7.8 g kg^{-1}) that significantly ($p \leq 0.05$) increased between 7.9 and 10.3 g kg^{-1} following the application of organic–inorganic amendments (except for UN, zeolites, and their combinations). The percent increase in SOM due to amendments varied between 1.2 and 32.0% (Table S1). The soil receiving the combinations of PM_{120} + Z_1 and PM_{120} + Z_2 displayed 30.4 and 29.1% increases in SOM content, respectively, compared to the sole application of Z_1 and Z_2.

The changes in total soil N (TSN) under different amendments showed a minimum TSN of 0.4 g kg^{-1} in the control soil that increased between 0.4 and 0.5 g kg^{-1} in the amended soil, exhibiting the relative increase of 0.1 to 27.9% over the control. The effect of UN, zeolites, and their combinations (UN + zeolites) on TSN was on par with the control (Table S1). However, the combination of PM and zeolites in PM_{120} + Z_1 and PM_{120} + Z_2 treatments increased TSN by 27.9 and 22.7%, respectively, over Z_1 and Z_2 alone. By combining the amendments in UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2 treatments, the TSN showed an increase of 11.4, 13.6, and 15.9%, respectively, over the control. Among different amendments, the combined application of PM_{120} + Z_1 recorded the highest TSN and was on par with PM_{120} + Z_2 and PM_{120} (Table S1).

Soil available phosphorus (SAP) in the control soil was 6.5 mg kg^{-1}, which increased between 6.8 and 9.2 mg kg^{-1} because of the application of organic–inorganic amendments (except for UN, zeolites, or their combinations). The relative increase in SAP for the amended soil varied between 5.6 and 41.7% (Table S1). The sole application of zeolites, UN_{120}, and their combinations showed non-significant differences with the control. The SAP in Z_1- and Z_2-amended soil was 10.4 and 11.5% higher compared with the control, respectively. The combination of PM with zeolites in PM_{120} + Z_1 and PM_{120} + Z_2 treatments further increased SAP by 27.9 and 27.0%, respectively, over Z_1 and Z_2 alone. In the combined N treatments (UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2), the SAP was 25.3, 23.9, and 28.6%, respectively, higher than that recorded in the control soil. The highest SAP was recorded in PM_{120} + Z_2 followed by PM_{120} + Z_1 and PM_{120} and the differences among the three were non-significant.

Soil extractable potassium (SEK) increased between 87 and 142 mg kg^{-1} under organic–inorganic amendments compared to the control (82 mg kg^{-1}). The percent increase (over control) in SEK varied between 6.0 and 73.1% among different amendments (Table S1). The treatments where UN and zeolites were applied alone or in combination did not significantly ($p \leq 0.05$) increase SEK. The soil amended with the combination of PM_{120} + Z_1 and PM_{120} + Z_2 recorded a 40.8 and 32.0% higher SEK, respectively, compared to the sole application of Z_1 and Z_2. The combination of half UN with PM + zeolites in treatments UN_{60} + PM_{60} + Z_1, UN_{60} + PM_{60} + Z_2, and UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2 did not significantly ($p \leq 0.05$) increase SEK over PM_{120} + Z_1 and PM_{120} + Z_2. However, the relative increase over the control was 40.2, 37.8, and 73.1%, respectively. The highest SEK was recorded in the treatment receiving the combination of UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2 followed by PM_{120} + Z_1 and the difference between the two was non-significant. Among the amendments, the relative increase for soil pH, SOM, total, available P, and extractable K varied between 3.1%, 1.2 and 32.0%, 0.1 and 27.9%, 5.6 and 41.7%, and 6.0 and 73.1%, respectively (Table S1).

4. Discussion

This study investigated the impact of nitrogen application strategies, focusing on urea (UN), poultry manure (PM), and zeolites, on wheat crop growth. The results revealed synergistic effects, indicating a cooperative influence on plant development. The increased root length of wheat recorded in our study for the combined treatments could be attributed to the greater uptake of nutrients and water and improved soil physical properties. The combination of UN and PM likely contributes to a more balanced nutrient profile for plant uptake [45]. PM, rich in organic matter, releases nutrients gradually, complementing the quick-release nature of urea [46]. Zeolites likely enhanced nutrient retention and reduced leaching, contributing to improved shoot and root development [47]. The combination of PM with zeolites may further support microbial populations, as zeolites have been reported to create a favorable environment for beneficial microorganisms [48].

This study provides evidence of the significant improvements in wheat yield and yield components through the application of urea, PM, and zeolites. The probable reason for the higher yield of wheat might be the role of nitrogen in plant metabolism that increases grain yield and the role of zeolite in nutrient retention and slow release in the root zone [49]. The maximum number of grains spike^{-1} of wheat recorded in our case for UN_{120} treatment is in accordance with the findings of Ali et al. [50], where they reported a significantly higher number of grains spike^{-1} from the treatment receiving a full application of chemical fertilizer. The results also showed that the combined application of UN with zeolites in UN_{120} + Z_1 and UN_{120} + Z_2 treatments increased the 1000-grain weight, straw yield, and grain yield over the control treatment. The positive effects of UN, zeolite, or their combinations on the 1000-grain weight and final crop yield have been reported in many of the experiments [51,52]. This suggests that the integration of nitrogen and organic amendments with zeolites can result in an enhanced overall plant performance and yield. The synergy may arise from an improved nutrient availability, optimized water retention, and balanced nutrient profile [47].

This study highlights the effectiveness of applied fertilizer treatments in enhancing nutrient content in wheat shoots and grains. Treatment UN_{120} significantly boosts nitrogen (N), phosphorus (P), and potassium (K) content, emphasizing the positive impact of this nitrogen application strategy on wheat nutrient accumulation. The observed improvements in nutrient content align with the known role of nitrogen in enhancing protein synthesis and overall plant growth [53]. The treatment PM_{120} also resulted in enhanced nutrient contents of shoot and grains. These findings suggest that PM not only contributes to nitrogen availability but also positively influences P and K levels, supporting the nutritional quality of the grains [54]. The combinations of UN and PM with zeolites (Z_1 and Z_2) further augmented nutrient levels in both shoots and grains. Among these combinations, the UN_{120} + Z_1 treatment stood out with the highest values for shoot N and grain K. The synergistic effects of combining N and P from PM and the nutrient-retaining properties of zeolites likely contribute to the observed increases in the nutrient content of shoots and grains [47,55].

The integrated application of UN, PM, and zeolites, either individually or in combination, significantly influenced nutrient uptake in wheat plants. The synergy observed in combined treatments highlights the potential of integrating nitrogen sources with organic amendments and zeolites to enhance N uptake in wheat shoots, leading to improved plant growth and nutrient content. Zeolites have been shown to reduce N leaching and volatilization, increase nutrient retention, and improve soil structure, thus contributing to an enhanced nutrient uptake and overall plant performance [56,57]. Zeolites alone did not bring a significant increase, but when combined with UN and PM, they contributed to enhanced P uptake [58]. The combination of PM with zeolites further increased K uptake, indicating the synergistic effects of organic matter and zeolites in improving K availability for wheat plants. The application of zeolites alone or with organic amendments improved crop quality by enhancing the retention of nutrients in the root zone for plant use [49]. Zeolite regulates the supply of nutrients from both organic and inorganic fertilizers, thereby increasing the efficiency of applied amendments [59]. Lija et al. [60] stated that zeolite-blended NPK fertilizers significantly affected the N, P, and K content and uptake of maize. They reported increased N, P, and K uptakes in maize grown under the combined application of zeolite and inorganic fertilizers in their experiment [16]. The positive effects of combining organic amendments with mineral N fertilizer on crop N, P, and K uptake were also reported by Martín-Lammerding et al. [61].

Organic amendments had positive effects on soil physicochemical properties, which, in turn, increased root development and nutrient absorption in crops [9]. The application of urea nitrogen (UN) led to a slight decrease in soil pH, attributed to the acidifying effect of urea hydrolysis, releasing ammonium ions (NH_{4+}) and increasing acidity [62]. Conversely, poultry manure (PM) application increased soil pH, likely due to the presence of alkaline materials and organic compounds that release hydroxide ions (OH^-) during decomposition [63]. The combination of PM with UN + zeolites further amplified the pH increase, suggesting a synergistic effect between PM and zeolites in promoting alkalinity. Zeolites have been reported to have a neutralizing effect on soil acidity by exchanging cations with the soil solution [64].

The application of organic amendments such as PM_{120} likely contributed to the increase in soil organic matter (SOM) content. PM serves as a substrate for microbial activity [46], supplying organic carbon and nutrients and contributing to increased SOM through microbial decomposition [63]. Other organic manures, such as farmyard manure (FYM), have also been reported to increase the concentration of organic matter in the soil [9,25]. Zeolites are known for their cation exchange capacity and ability to improve soil structure [20]. However, in this specific study, the sole application of zeolites (Z_1 and Z_2) did not lead to a significant increase in SOM. This could be due to zeolites having a limited role in directly providing organic carbon [21]. Their impact on SOM might be more indirect through influences on nutrient availability and microbial activity [51]. The integrated application of PM and zeolites (PM_{120} + Z_1 and PM_{120} + Z_2) led to significant increases in SOM content. This might be attributed to the synergistic effect. PM could be supplying organic carbon [46], while zeolites enhance soil structure and possibly promote microbial activity [64]. This combination may create a favorable environment for SOM accumulation.

The marginal impact on total soil nitrogen (TSN) from UN and zeolite applications suggests their limited contribution to soil nitrogen content. However, the combined use of poultry manure (PM) and zeolites results in a significant rise in TSN. PM, rich in nitrogen, contributes to an additional nitrogen pool through organic nitrogen compound mineralization [65]. Zeolites, known for cation exchange and slow nutrient release, enhance nutrient use efficiency and mitigate leaching losses [20]. The synergy between PM and zeolites combines an immediate nitrogen source from organic matter with sustained release, as supported by various studies on zeolite-amended soils [48,66,67].

In this study, zeolites and urea alone had minimal impact on soil available phosphorus (SAP), potentially due to zeolites selectively adsorbing other cations over phosphorus [68]. However, the combination of PM with zeolites (PM_{120} + Z_1 and PM_{120} + Z_2) showed a substantial increase in SAP over Z_1 and Z_2 alone. This synergistic effect is attributed to PM's organic matter content, stimulating soil microbial activity [63]. The published literature supports the idea that combining zeolite with chemical fertilizer can reduce ammonia loss, enhance nutrient efficiency, and allow a gradual nutrient release from both organic and inorganic sources [69]. Zeolites do not easily break down over time, and therefore, they remain in the soil to improve nutrient retention [70].

The highest levels of soil-exchangeable potassium (SEK) were observed with the integrated application of urea (UN), poultry manure (PM), and zeolites (UN_{60} + PM_{60} + ½ Z_1 + ½ Z_2), indicating that a balanced blend of organic and inorganic amendments maximizes K availability [63]. This synergy involves the mineralization of organic matter from PM, zeolites' ion-exchange capacity, and the nitrogen contribution from urea, indirectly enhancing soil microbial activity and potassium availability [20]. Organic amendments, such as manure compost, have been found to significantly increase soil-exchangeable K and the relative abundance of *Lysinibacillus*, a potassium-solubilizing bacterium [71]. Compost decomposition releases basic cations like K, contributing to soil potassium availability [72]. Furthermore, repeated compost applications enhance soil potassium levels by decreasing fixation, increasing cation exchange capacity (CEC), and retaining a higher amount of exchangeable potassium on the exchange complex [73].

5. Conclusions

The combined application of urea nitrogen (UN), poultry manure (PM), or their combinations with zeolites demonstrated significant impacts on increased wheat growth, yield, and nutrient uptake. Regarding soil attributes, organic amendments, particularly PM alone or in combination with additional N sources (UN and zeolites), significantly enhanced the soil organic matter content, total N, accessible P, and extractable K. These findings affirm that the organic sources used in this study, when applied in conjunction with half urea N and zeolites, yielded results equivalent to full UN treatments across most parameters. Consequently, it is recommended to integrate mineral nitrogen sources with organic sources as a successful strategy for maximizing wheat production. However, it is crucial to acknowledge the limitations of this study. The current research is based on a one-year study, and therefore, caution is advised in making widespread recommendations. Future research endeavors should aim to conduct comprehensive, long-term studies to further validate and extend the findings observed in this limited timeframe. In terms of future directions, subsequent studies could explore the temporal dynamics of the observed effects and investigate potential variations under diverse environmental conditions. Additionally, an in-depth analysis of the economic feasibility and sustainability of the proposed strategies would contribute valuable insights for practical agricultural applications.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/soilsystems8010018/s1. Table S1: Effect of UN, PM, and zeolite on pH, organic matter content, total N, available P, and extractable K of post-harvest soil.

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