Pol. J. Environ. Stud. Vol. 35, No. 5 (2026), 6095-6109
DOI: *10.15244/pjoes/211157* ONLINE PUBLICATION DATE: 2025-11-12

Original Research

Integrated Application of Enriched Compost and Chemical Fertilizers Improves Soil Fertility, Zinc Biofortification, and Cucumber Productivity

Muhammad Munir Anjum[1], Muhammad Fakhar U Zaman Akhtar[1]*, Maqshoof Ahmad[1], Azhar Hussain[1], Zafar Iqbal[2], Ahmed Mahmoud Ismail[3], Sherif Mohamed Elganainy[4], Hossam S. El-Beltagi[5], Hossam M. Darrag[6], Maha Loutfi Hadid[7]**

[1]Department of Soil Science, The Islamia University of Bahawalpur, 63100, Bahawalpur, Pakistan
[2]National Research Center of Intercropping, The Islamia University of Bahawalpur, 63100, Bahawalpur, Pakistan
[3] Pests and Plant Diseases Unit, College of Agricultural and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia
[4]Department of Arid Land Agriculture, College of Agricultural and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia
[5]Agricultural Biotechnology Department, College of Agricultural and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia
[6]Research and Training Station, King Faisal University, Al-Ahsa 31982, Saudi Arabia
[7]Department: Agribusiness and Consumer Sciences, College of Agricultural and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia

Received: 14 May 2025
Accepted: 21 September 2025

Abstract

Integrated Nutrient Management (INM) enhances crop productivity and nutritional quality while preserving soil health. This study evaluated the impact of the integrated application of enriched compost derived from organic waste and chemical fertilizers on cucumber (*Cucumis sativus*) growth, yield, and zinc (Zn) biofortification under pot conditions. A total of six treatments were tested: T1 (control), T2 (chemical fertilizers: urea + diammonium phosphate (DAP) + sulfate of potash (SOP)), T3 (zinc coated urea (zabardast urea) + DAP + SOP), T4 (zinc-enriched compost), T5 (zinc-enriched compost + chemical fertilizers), and T6 (zinc-enriched compost + Zabardast urea + DAP + SOP). The integrated treatment (T6: enriched compost + Zabardast urea + DAP + SOP) outperformed others, improving seed germination (27%), seed vigor index (56%), chlorophyll content (54%), and key biochemical parameters: carbohydrates (30%), soluble sugars (18%), protein (26%), and fiber (20%). Morphological traits such as vine length (22%), stem girth (65%), number of leaves per plant (42%), and fruit yield (8%) were also highest under T6. Furthermore, soil analysis after harvest revealed a substantial increase in organic

*e-mail: fakhar286@gmail.com
** e-mail: amismail@kfu.edu.sa

© 2026 This article is licensed under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0)

matter and the availability of macronutrients (nitrogen, phosphorus, and potassium) and micronutrients (zinc and iron). Principal component analysis (PCA) and correlation analysis confirmed strong positive associations between improved soil fertility and cucumber performance. These results underscore the potential of enriched compost derived from organic waste in recycling nutrients and reducing reliance on synthetic inputs. The integrated use of enriched compost and chemical fertilizers (T6) represents a sustainable, climate-resilient nutrient management strategy to enhance soil health, crop productivity, and nutritional value.

Keywords: biofortification, cucumber quality, enriched compost, integrated nutrient application, organic waste

Introduction

Vegetables play a pivotal role in human nutrition due to their rich content of phytochemicals, including fiber, vitamins, antioxidants, and minerals. As a member of the Cucurbitaceae family, cucumber (*Cucumis sativus*) is an important vegetable with significant dietary and economic value. In Pakistan, cucumbers are one of the most widely consumed salad vegetables. Globally, cucumbers rank as the fourth most important vegetable after tomatoes, cabbage, and onions, cultivated both as a seasonal and a commercial crop. Their versatility enables their consumption in various forms, including fresh salads, pickles, and even as cooked dishes, depending on regional culinary preferences [1]. Cucumber (*Cucumis sativus L.*) is an important vegetable crop cultivated worldwide for its nutritional and economic significance [2]. However, sustaining high productivity and improving its micronutrient content, particularly zinc (Zn), is a major concern due to nutrient imbalances and declining soil fertility [3]. Zinc plays a vital role in photosynthesis, enzyme activation, and overall plant growth. A deficiency can lead to severe yield losses and reduced crop quality, making zinc biofortification a key agricultural goal. Integrated Nutrient Management (INM), which combines organic and inorganic nutrient sources, has gained attention as a sustainable approach to enhancing crop productivity and nutritional quality [4, 5].

The nutrient composition of cucumbers is notable, with their high water content resulting in only 15 calories per cup. Despite their low caloric value, cucumbers are packed with health benefits, including antioxidant and anti-inflammatory properties and potential benefits for managing diabetes. Additionally, cucumber seeds relieve constipation and help regulate body temperature [6]. Global cucumber production was estimated at 83.7 million tons annually, while Pakistan contributed 54.29 thousand tons in 2016, with an average yield of 16 t/ha from 3.38 t/ha of cultivated area [7]. Several factors, including soil nutrient availability, climate, genotype, and cultural practices, influence cucumber production and nutritional quality. Among these, the role of nitrogen-fixing bacteria and the homogeneous distribution of essential nutrients like nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), iron (Fe), and sulfur (S) in the soil are particularly crucial. In Pakistan, the uneven distribution of these nutrients poses a significant challenge, impacting crop yield and quality [8].

Malnutrition remains a global public health challenge, particularly in developing nations [9]. According to the World Health Organization (WHO), malnutrition arises when the essential nutrients and energy are inadequate for normal cellular function, growth, and repair. This condition includes deficiencies in macronutrients, such as protein and calories, and micronutrients like zinc, iron, iodine, selenium, and vitamin A [10]. Zinc deficiency is a pressing concern; it affects approximately 17% of the global population, including 40% of pregnant women and 42% of children under five years [11]. Consequences of zinc deficiency range from impaired growth and neuropsychological functions to immune disorders, delayed sexual maturation, and chronic infections [12].

Soil zinc deficiency is a widespread problem, particularly in Pakistan, India, China, and Turkey [13]. Zinc availability in soil is influenced by its solubility, which is often limited despite adequate total zinc levels [14]. This deficiency affects crop productivity, with mild soil zinc deficiencies leading to yield losses of up to 30% in cereal crops such as wheat, rice, and maize [15]. Dicots, including cucumbers, are also significantly impacted. In cucumbers, zinc deficiency can lead to up to a 40% reduction in total root length, severely impairing water and nutrient uptake. Addressing zinc deficiency in crops requires the development of effective biofortification strategies. Recent research highlights the potential of agronomic biofortification to enhance zinc concentrations in crops through integrated nutrient management [16, 17]. Factors such as the type of zinc fertilizer, application method, timing, and environmental conditions play critical roles in determining the success of these interventions.

Forecasts suggest that the global population will reach 9.8 billion by 2050, further intensifying the challenge of malnutrition. Addressing zinc deficiency is critical, as sufficient zinc intake improves growth and reduces disease prevalence, particularly in children from low-income regions [3]. Zinc is an essential micronutrient for both plants and humans. It plays a vital role in numerous physiological processes, including

photosynthesis, growth regulation, disease resistance, and enzyme activation [18, 19]. Zinc deficiency in plants leads to growth retardation, reduced root development, and reduced yield. For instance, zinc-deficient cucumbers exhibit a 39.9% reduction in total root length [20]. Given its importance, enhancing the zinc content of crops through biofortification has become a focus of agricultural research.

Biofortification, the process of enriching crops with essential minerals, is a promising approach to addressing micronutrient deficiencies in human diets. This can be achieved through two primary strategies: genetic biofortification, involving conventional breeding or transgenic techniques, and agronomic biofortification, which involves the application of nutrients at specific stages of crop growth [21]. Agronomic biofortification is a cost-effective and accessible method, particularly in developing countries. It involves techniques such as integrated nutrient management (INM), seed priming, and seed coating to increase the nutrient density of crops.

Among the INM strategies, the integrated application of enriched compost and chemical fertilizers has gained attention as a promising alternative to conventional nutrient management. Enriched compost improves soil physical, chemical, and biological properties by enhancing organic matter and microbial activity, which increases nutrient availability and supports long-term soil fertility [22, 23]. On the other hand, chemical fertilizers provide readily available nutrients but may lead to soil acidification, nutrient leaching, and long-term soil fertility decline [24]. This dual approach allows for the synergy between immediate nutrient availability and long-term soil health, providing a balanced solution for sustainable agriculture.

Despite its potential, the comparative advantages and limitations of integrating enriched compost with chemical fertilizers remain insufficiently explored, especially in the context of zinc biofortification in cucumbers. Thus, a comprehensive assessment of this integrated approach is required to understand its role in crop productivity, nutritional enhancement, and environmental sustainability. This study evaluates the impact of enriched compost and chemical fertilizers on cucumber productivity and Zn biofortification. By comparing these nutrient management approaches, the present work provides novel insights into a sustainable solution to micronutrient deficiency and declining soil fertility, contributing to improved food security, nutritional health, and agricultural sustainability.

Materials and Methods

Collection of Fertilizers

The diammonium phosphate (DAP: 18% N and 46% P), Urea (46% N), and sulfate of potash (SOP: 50% K) were bought from the local market. Another source of N "Zabardasat Urea" (42% N, 3% Zn) manufactured by Engro Fertilizers Limited, Pakistan, was also used for comparison with Urea.

Preparation of Zinc-Enriched Compost

Zinc-enriched compost was prepared in a composting unit at the Department of Soil Science, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur. For this purpose, domestic organic waste was collected, air-dried under shade following drying in the oven at 65 °C, and ground using a grinding machine (flour mill). Then, the ground organic material was filled into a composting drum along with 40% water and 1% urea to enhance the composting process [25]. The drum will be continuously rotated for up to three weeks using an electric motor to mix the material homogeneously. The compost was enriched with zinc (Zn) by adding zinc oxide (ZnO) at a rate of 2% by weight. Another zinc source used in the study was zinc-coated urea (Zabardast Urea), a product of Engro Fertilizer Company Limited, Pakistan, which contains 42% nitrogen (N) and 1% bioactive zinc. A composite sample of enriched compost was collected and analyzed. The compost exhibited a moisture content of 38%, an electrical conductivity (EC) of 1.16 dS m^{-1}, and a slightly alkaline pH of 7.83. Increasing pH can drive the solubilization of organic matter from wetland soils, particularly under reducing conditions [26]. It contained a high organic matter (38%) and total organic carbon content (63%). Chemical analysis revealed the presence of 183 mg kg^{-1} of extractable potassium (K), 19 mg kg^{-1} of available phosphorus (P), and 2.96% total nitrogen. The enriched compost showed elevated levels of DTPA-extractable micronutrients, including 32 mg kg^{-1} of zinc (Zn) and 9.7 mg kg^{-1} of iron (Fe). A microbial count of 39×10^6 CFU g^{-1} soil indicated robust microbial activity in the compost.

Pot Trial

The pot trial was conducted in the wire-house of the Department of Soil Science, the Islamia University of Bahawalpur, under natural climatic conditions. Bahawalpur (29.3544º N, 71.6911º E) is a district in the Punjab province of Pakistan, located in the southern region at the edge of the Cholistan Desert. The area has an arid climate, with annual rainfall of less than 150 mm, most of which occurs during the monsoon season (mid-July to mid-September). The cucumber crop was sown in the first week of March and harvested in the third week of May in 2024. The average temperature and rainfall during the cropping period are shown in Fig. 1. The soil was air-dried under shade, ground, and sieved through a 2 mm mesh size sieve to remove gravel. The soil was analyzed for physicochemical characteristics. The pot capacity of 12 kg of dried soil was used for this experiment. The treatments were applied as different fertilizer combinations, i.e., T_1: absolute control, T_2:

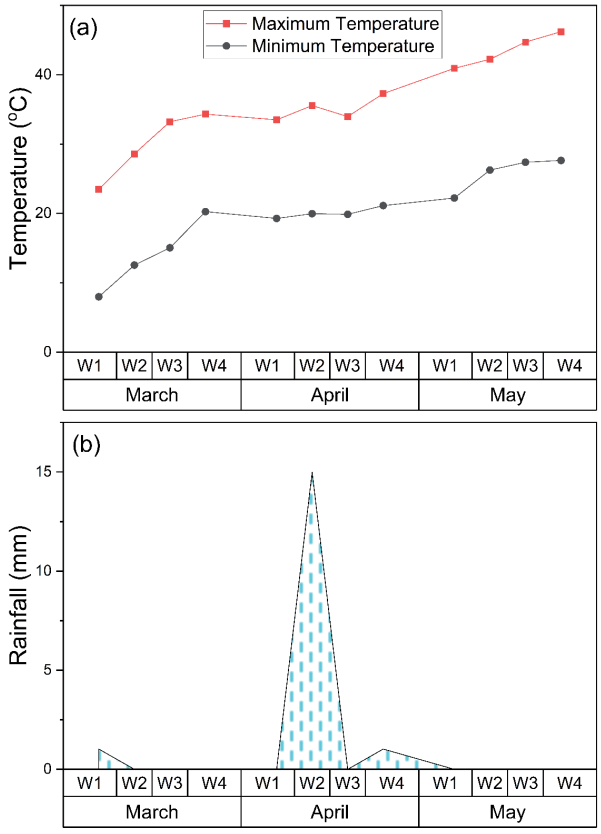

Fig. 1. Climate conditions include maximum and minimum temperature (a) and rainfall (b) during the cropping season in 2024. The data is presented as an average of a week (W).

Urea + DAP + SOP, T_3: Zabardast urea + DAP + SOP, T_4: Zn-enriched compost, T_5: Zn-enriched compost + Urea + DAP + SOP, T_6: enriched compost + Zabardast urea + DAP + SOP. The mentioned fertilizers will be applied to meet the recommended NPK doses @ 100:50:50 kg ha^{-1}. The pots were arranged in a completely randomized design (CRD) and replicated three times. Ten cucumber seeds were sown in each pot. After germination, five plants per pot were maintained; good-quality tap water was used for irrigation. Agronomic practices were carried out according to need. The crop was harvested to measure the yield and quality parameters.

Soil Analysis

Pre-sowing and post-harvesting soil samples were collected, air-dried in the shade, ground, thoroughly mixed, and sieved through a 2 mm mesh size. The available Zn was measured by extracting with diethylenetriaminepentaacetic acid (DTPA), and zinc concentration was measured by an atomic absorption spectrophotometer [27]. To determine the total N, Olsen P, and extractable K, the protocol described by Ryan et al. [28] was followed. Organic matter in the soil was determined by the method of Moodie et al. [29]. To determine the organic matter, one gram of soil was mixed with 10 mL of potassium dichromate solution, followed by the addition of 20 mL of concentrated sulfuric acid, and left for 30 minutes. About 150 mL of deionized water and 25 mL of ferrous sulfate (0.5 N) were added. The mixture was titrated till the pink endpoint. The saturation percentage was determined by measuring the weight of the saturated soil paste and comparing it to the oven-dried weight of the same soil sample.

Plant Analyses

The SPADE values were measured from the leave sample after 60 days [30]. Other parameters, like growth and yield, were determined after harvesting. The analysis of N, P, and K was conducted for cucumber fruits.

Biochemical Analysis

Total carbohydrates were determined using the phenol-sulfuric acid technique, where cucumber extracts were processed, broken down with sulfuric acid, and combined with phenol before analyzing absorbance at 490 nm with a spectrophotometer [31]. Dietary fiber levels, comprising both insoluble and soluble components, were evaluated using the enzymatic-gravimetric procedure, which included sequential enzyme treatment with α-amylase, protease, and amyloglucosidase, followed by filtering, drying, and measuring the remaining material [32]. For spectrophotometric analysis of soluble sugars, 1 g of the sample is blended with hexane. Heat this mixture in a water bath maintained at 80–90°C for approximately 30 minutes to facilitate complete sugar extraction. Vortex the tube for 1 minute and subject the mixture to centrifugation at 13000 rpm for 15 minutes, and collect the resulting supernatant. The supernatant was discarded, and 5 mL of 80% ethanol solution was added to precipitate. After vortexing for 1 minute, the tubes were centrifuged at 13000 rpm for 10 minutes. Supernatant was filtered in an Eppendorf tube and preserved at 4°C for further analysis [33]. Sugar levels are measured using a color-based technique through the anthrone procedure. In the anthrone method, combine 50 µL of the extract with 5 mL of anthrone reagent (dissolve 2 g of anthrone in 1 L of concentrated H_2SO_4), vortex the mixture for 1 minute, and then heat in a water bath (95°C) for 10 minutes. Let the mixture cool to room temperature before measuring its absorbance at 620 nm using a spectrophotometer. Calculate sugar concentrations by comparing readings against a standard curve created using known glucose solutions.

Protein analysis was conducted using the Kjeldahl method, following the guidelines set by the Association of Official Analytical Chemists [34]. For this purpose, 1 g portion of the homogenized sample was placed into a Kjeldahl digestion flask, with three boiling beads, 10 g of potassium sulfate, and 20 ml of concentrated sulfuric acid. The mixture was heated until it became clear, then allowed to cool before adding 200 ml

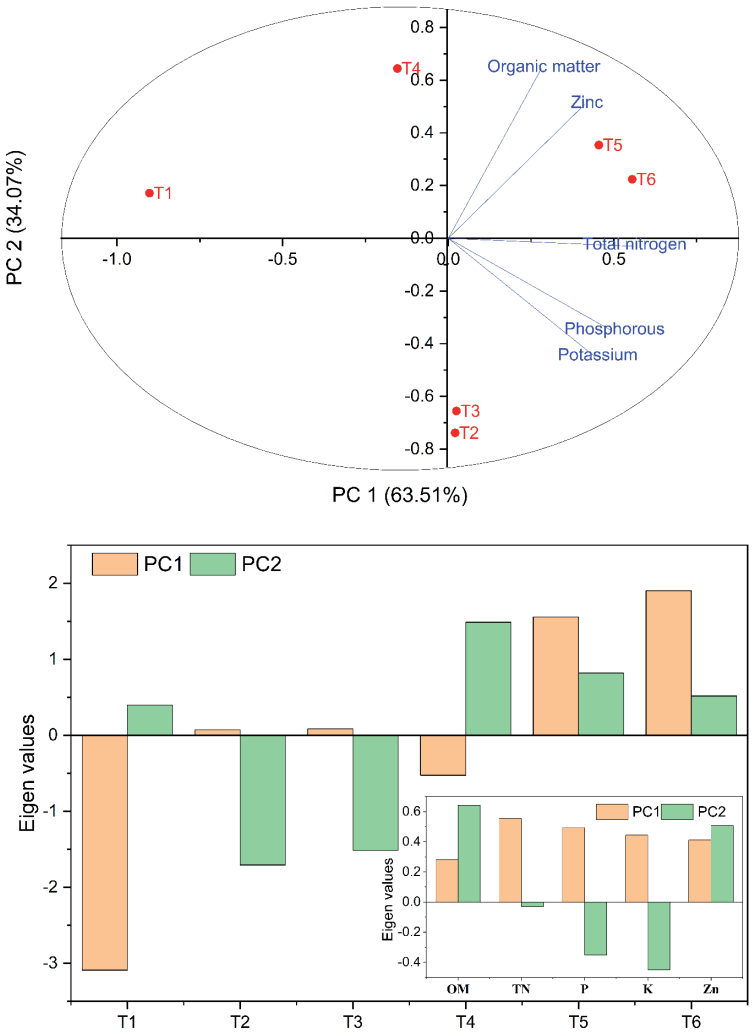

Fig. 2. Principal component analysis (PCA) showed the impact of integrated application of enriched compost and chemical fertilizers on soil health. T_1: control; T_2: Urea + DAP + SOP; T_3: Zabardast urea + DAP + SOP; T_4: Zn enriched compost; T_5: Zn enriched compost + Urea + DAP + SOP; T_6: enriched compost + Zabardast urea + DAP + SOP.

of tri-distilled water. After the addition of 20 mL of 40% sodium hydroxide, the solution was connected to a distillation apparatus. The distillation continued until at least 70 ml of the distillate was collected in a receiving flask containing 20 ml of 4% boric acid. The sample was then titrated using 0.1 N sulfuric acid. The final protein content was calculated by multiplying the obtained value by a conversion factor of 6.25 and expressed as a percentage. All tests were conducted three times to ensure reliable and consistent results.

Macronutrient Determination

The plant sample was subjected to sulfuric acid digestion, using K_2SO_4: $CuSO_4$: $FeSO_4$ (10: 05: 01) digestion mixture. The sample was prepared by grinding 1 gram of the dried sample into powder and then adding it to a Kjeldahl digestion flask, followed by 10 ml of concentrated sulfuric acid and 0.1 g of the digestion mixture, and left for 30 minutes. After transferring the digestion flasks to the stove, the sample was heated gradually at 100ºC and then increased to 350ºC. After cooling at room temperature, the contents were transferred to a 100 ml volumetric flask, and the volume was made up with distilled water. The macronutrients (N, P, and K) were measured using the standard protocol [28].

Nitrogen was determined by the Kjeldahl method. For distillation, 10 ml of the digested solution was taken in the Kjeldahl flask and placed in the distillation block with 10 ml NaOH (40%). In a 100 ml flask, a few drops of the mixed indicator were added with 10 ml of boric acid (4%) to collect the distillate up to 30-40 ml. The distillate was titrated against 0.01 N sulfuric acid till the pink endpoint. A spectrophotometer was used to measure phosphorus at 420 nm after being calibrated against P standards. The potassium standard curve was made by knowing the concentration standards prepared, using potassium chloride. Digested plant samples were analyzed on a flame photometer (Jenway, PFP-

7). A standard curve was used for the calculation of K^+ concentrations

Determination of Zinc

Tri-acid digestion was used to ascertain the micronutrient content [35]. Take 0.1 g dry fruit sample followed by 25 ml of triazide mixture (1 L of concentrated HNO3, 100 ml of concentrated HCl, 25 ml of concentrated H_2SO_4), which was then placed in a 250 mL beaker containing boiling beads. After that, the sample was heated over a digester grill in a fume hood. After the reaction, the samples were filtered into 50 ml volumetric flasks (stock solution), and the volume was made up to the mark with triple-distilled water. Atomic absorption spectrophotometry was used to determine the zinc concentrations. Zn concentration was calculated by comparing the samples' readings with a calibration curve, developed using 0, 2, 4, 6, 8, and 10 mg kg^{-1} Zn standards.

Statistical Analysis

The data were statistically analyzed using the analysis of variance (ANOVA) technique. The treatment means were compared using LSD at a 5% probability level. Principal component analysis (PCA), parallel diagram analysis, and chord diagram analysis were carried out using Origin Pro 2021 (b).

Results

Impact of Enriched Compost and Different Chemical Fertilizers on Soil Characteristics

The principal component analysis (PCA) revealed the influence of treatments on soil parameters, including organic matter (OM), total nitrogen (TN), phosphorus (P), potassium (K), and zinc (Zn) (Fig. 2). The eigenvalues for PC1 and PC2 highlighted the contributions of soil parameters to the variation explained by the components. PC1 accounted for the highest variation in the dataset, with organic matter (OM) contributing significantly (loading = 0.28128) along with total nitrogen (TN, loading = 0.56), phosphorus (P, loading = 0.49), potassium (K, loading = 0.44), and zinc (Zn, loading = 0.41218). This indicates a broad influence of multiple soil parameters on PC1. In contrast, PC2 showed strong contributions from OM (loading = 0.64) and Zn (loading = 0.51), suggesting that these parameters significantly differentiate treatments along this component. Treatment T1 (absolute control) was distinctly separated along PC1, showing negative eigenvalues (-3.09 for PC1), reflecting its low levels of OM (0.55%), TN (0.04%), P (6.56 mg/kg), K (82 mg/kg), and Zn (0.6 mg/kg). Treatments involving compost (T4, T5, and T6) clustered toward the positive end of PC1, indicating their enrichment in OM, TN, P, K, and Zn. T6 (enriched compost + Zabardast Urea + DAP + SOP) had the highest TN (4.78%) and Zn (2.31 mg/kg), along with significant levels of OM (3.05%), P (9.38 mg/kg), and K (87.2 mg/kg), contributing to its high eigenvalue (1.90) for PC1. Overall, the PCA analysis emphasizes that treatments incorporating Zn-enriched compost (T4, T5, T6) improve soil fertility parameters, especially OM, TN, and Zn, while chemical fertilizer treatments (T2, T3) show moderate effects. These results underscore the potential of integrated nutrient management for enhancing soil health.

Impact of Enriched Compost and Different Chemical Fertilizers on Seed Germination and Seedling Growth

The study evaluated the influence of various treatments on SPAD value, seed germination percentage, seed vigor index I, and seed vigor index II. The results revealed that these parameters were significantly affected by the applied treatments (Fig. 3). Among the treatments, T6 (enriched compost + Zabardast urea + DAP + SOP) showed the highest performance across all parameters, with an SPAD value of 25.57, seed germination of 86.20%, seed vigor index I of 1418.33, and seed vigor index II of 13.70. This was closely followed by T5 (Zn-enriched compost + Urea + DAP + SOP), which recorded an SPAD value of 24.77, seed germination of 84.20%, seed vigor index I of 1396.00, and seed vigor index II of 12.87. The treatment T4 (Zn-enriched compost) also demonstrated notable results, achieving an SPAD value of 23.53, seed germination of 78.00%, seed vigor index I of 1355.33, and seed vigor index II of 12.13. On the other hand, treatments T3 (Zabardast urea + DAP + SOP) and T2 (Urea + DAP + SOP) produced moderate outcomes, with T3 showing slightly better results than T2. The treatment T3 recorded an SPAD value of 18.93, seed germination of 72.83%, seed vigor index I of 1223.00, and seed vigor index II of 9.80, while T2 exhibited an SPAD value of 18.67, seed germination of 70.97%, seed vigor index I of 1210.33, and seed vigor index II of 9.23. The control treatment (T1) recorded the lowest values for all parameters, with an SPAD value of 16.50, seed germination of 67.67%, seed vigor index I of 1100.00, and seed vigor index II of 8.73. These findings highlight the significant impact of integrated nutrient management, particularly the combination of enriched compost with chemical fertilizers, in enhancing seed performance and chlorophyll content.

Impact of Enriched Compost and Different Chemical Fertilizers an Cucumber Growth

The study evaluated the effects of different fertilizer treatments on various plant growth and yield parameters. The results showed a progressive improvement in all parameters with increasing complexity and nutrient enrichment of the treatments (Table 1). Among the treatments, T6 consistently demonstrated superior

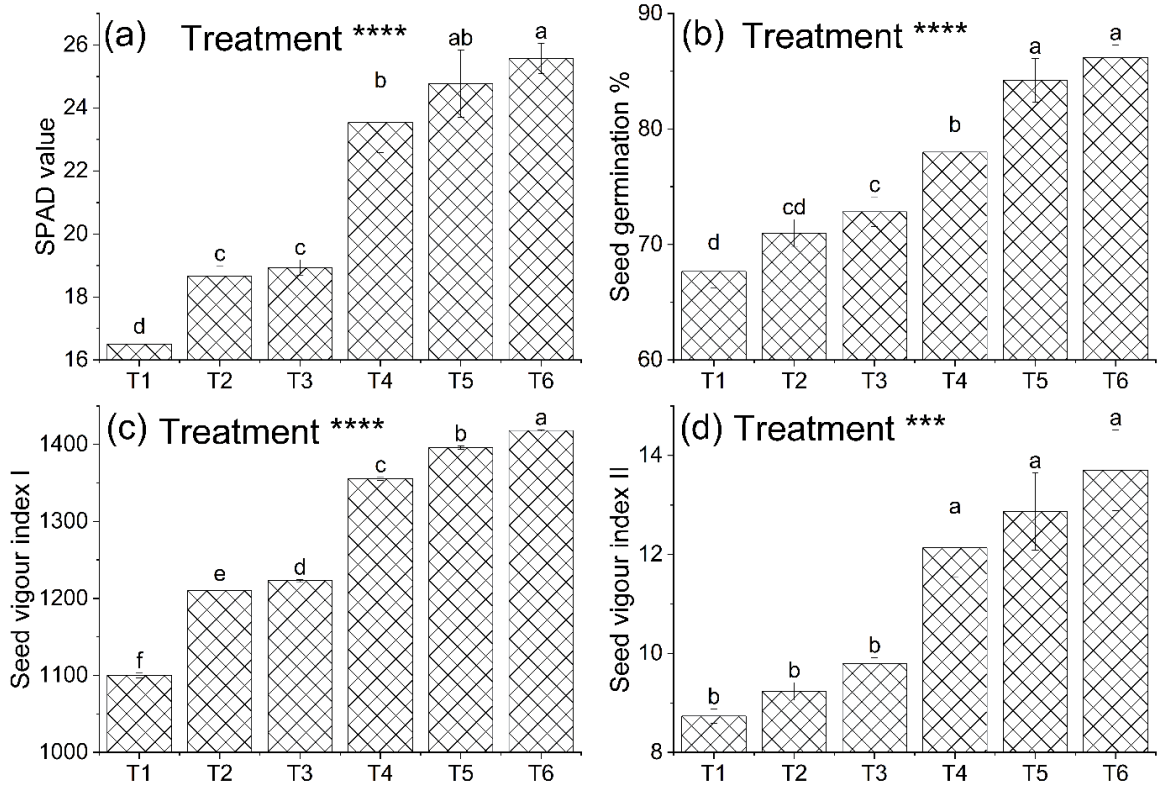

Fig. 3. Effect of integrated application of enriched compost and chemical fertilizers on SPAD value, seed germination, and seedling growth. Data presented as the mean of three replicates. Bars sharing the same letter(s) do not differ significantly at a 5% probability level ($p \leq 0.05$). (a): SPAD value; (b): seed germination percent; (c): Seedling vigor index I; (d): seedling vigor index II; *** $p<0.001$; **** $p<0.0001$; T_1: control; T_2: Urea + DAP + SOP; T_3: Zabardast urea + DAP + SOP; T_4: Zn enriched compost; T_5: Zn enriched compost + Urea + DAP + SOP; T_6: enriched compost + Zabardast urea + DAP + SOP.

Table 1. Integrated application of enriched compost and chemical fertilizers improves morphology, growth and yield of cucumber.

Treatment	Vine length (cm)	Vine Girth (mm)	Number of leaves per plant	Number of fruits per plant	Fruit length (cm)	Fruit diameter (cm)	100-seed weight (g)	Seed yield (g pot^{-1})
T_1	171 ± 1.7 c	3.02 ± 0.06 d	12.0 ± 0.7 c	1.33 ± 0.03 e	16.6 ± 0.8 b	6.60 ± 0.32 c	2.25 ± 0.104 a	15.7 ± 1.2 c
T_2	176 ± 1.6 c	3.52 ± 0.04 c	14.0 ± 0.6 bc	1.67 ± 0.09 d	17.7 ± 1.2 b	6.83 ± 0.32 c	2.30 ± 0.100 a	17.5 ± 1.0 c
T_3	179 ± 2.9 c	3.83 ± 0.09 c	14.7 ± 0.9 abc	2.00 ± 0.10 c	21.1 ± 0.7 a	7.33 ± 0.29 bc	2.34 ± 0.095 a	18.9 ± 1.3 bc
T_4	193 ± 5.6 b	4.30 ± 0.12 b	15.3 ± 0.9 ab	2.67 ± 0.12 b	20.6 ± 0.3 a	7.90 ± 0.45 ab	2.41 ± 0.099 a	21.0 ± 0.9 ab
T_5	201 ± 2.5 ab	4.53 ± 0.15 b	16.0 ± 0.6 ab	2.67 ± 0.15 b	21.7 ± 0.7 a	8.10 ± 0.12 ab	2.45 ± 0.110 a	23.0 ± 0.4 a
T_6	209 ± 1.0 a	4.97 ± 0.18 a	17.0 ± 1.2 a	3.00 ± 0.06 a	22.8 ± 1.3 a	8.57 ± 0.12 a	2.51 ± 0.110 a	23.5 ± 1.1 a
LSD ($p \leq 0.05$)	9.0794 ****	0.3551 ****	2.5159 *	0.3024 ****	2.7505 **	0.9071 **	0.3180 ^{ns}	3.2055 ***

Note: Data is presented as the mean of three replicates ± standard error. Columns sharing the same letter(s) do not differ from each other at 5 % probability level. * $p<0.05$; ** $p<0.01$; *** $p<0.001$; **** $p<0.0001$; ^{ns} non-significant; T_1: control; T_2: Urea + DAP + SOP; T_3: Zabardast urea + DAP + SOP; T_4: Zn enriched compost; T_5: Zn enriched compost + Urea + DAP + SOP; T_6: enriched compost + Zabardast urea + DAP + SOP

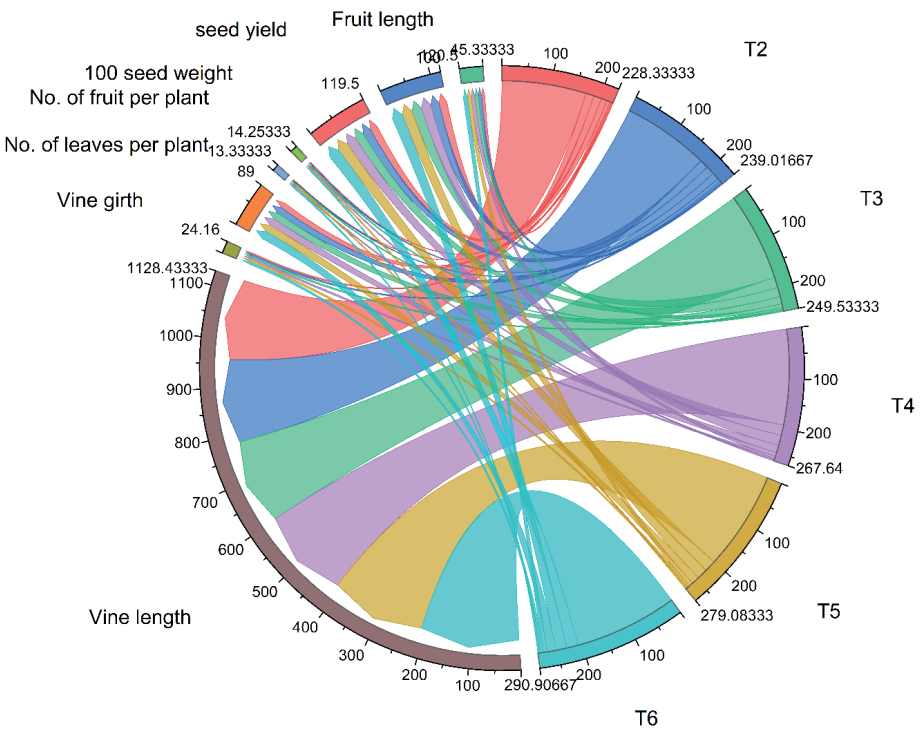

Fig. 4. A chord diagram analysis showed the correlation effect of different treatments of integrated application of enriched compost and chemical fertilizers on cucumber growth and fruit size. T_1: control; T_2: Urea + DAP + SOP; T_3: Zabardast urea + DAP + SOP; T_4: Zn enriched compost; T_5: Zn enriched compost + Urea + DAP + SOP; T_6: enriched compost + Zabardast urea + DAP + SOP.

performance across all parameters. The highest vine length (208.6 cm), vine girth (4.97 cm), number of leaves per plant (17), number of fruits per plant (3), seed yield (23.5 g), fruit length (22.77 cm), and fruit width (8.57 cm) were recorded in T6, highlighting its effectiveness. In comparison, T1 (absolute control) exhibited the lowest values for all measured traits, with vine length (170.9 cm), vine girth (3.02 cm), number of leaves per plant (12), number of fruits per plant (1.33), seed yield (15.67 g), fruit length (16.57 cm), and fruit width (6.6 cm), indicating the necessity of nutrient supplementation for optimal growth. Treatments with Zn-enriched compost, particularly T5 and T6, showed significant enhancements in vine girth, number of fruits per plant, and overall seed yield compared to treatments lacking compost (T2 and T3). For instance, T5 recorded a seed yield of 23 g and T6 recorded 23.5 g, outperforming T3 (18.87 g) and T2 (17.47 g). Additionally, the inclusion of Zabardast urea in T3 and T6 led to marked improvements in fruit dimensions and overall seed yield, signifying its beneficial role in nutrient delivery.

The chord diagram interpretation clearly illustrates strong positive correlations between seed yield and parameters such as vine girth, fruit length, and fruit width, with treatments T5 and T6 forming clusters indicative of superior nutrient efficiency (Fig. 4). These findings suggest that the integration of enriched compost and advanced urea formulations, as in T6, provides a synergistic effect that enhances plant growth and yield.

Impact of Enriched Compost and Different Chemical Fertilizers on Biochemical Characteristics of Cucumber

The results of the study indicated that the treatments significantly influenced the parameters of total soluble sugars, carbohydrates, total soluble protein, and fiber content (Fig. 5). Among the treatments, T1 (absolute control) exhibited the lowest values across all parameters. The treatment T6 (enriched compost + Zabardast urea + DAP + SOP) consistently recorded the highest values, with total soluble protein at 8.5 mg g^{-1} dry weight (DW), carbohydrates at 41.8 mg g^{-1} DW, total soluble sugar at 18.8 mg g^{-1} DW, and fiber content at 5.7 mg g^{-1} DW. The treatments T2 (Urea + DAP + SOP) and T3 (Zabardast urea + DAP + SOP) showed moderate improvements compared to the control, with T3 slightly outperforming T2 in all parameters. The treatments T4 (Zn-enriched compost) and T5 (Zn-enriched compost + Urea + DAP + SOP) further enhanced the measured parameters, with T5 showing superior performance over T4. Overall, the combination of Zn-enriched compost and Zabardast urea with DAP and SOP (T6) proved to be the most effective treatment in enhancing all evaluated parameters, demonstrating the synergistic effects of these inputs on crop quality.

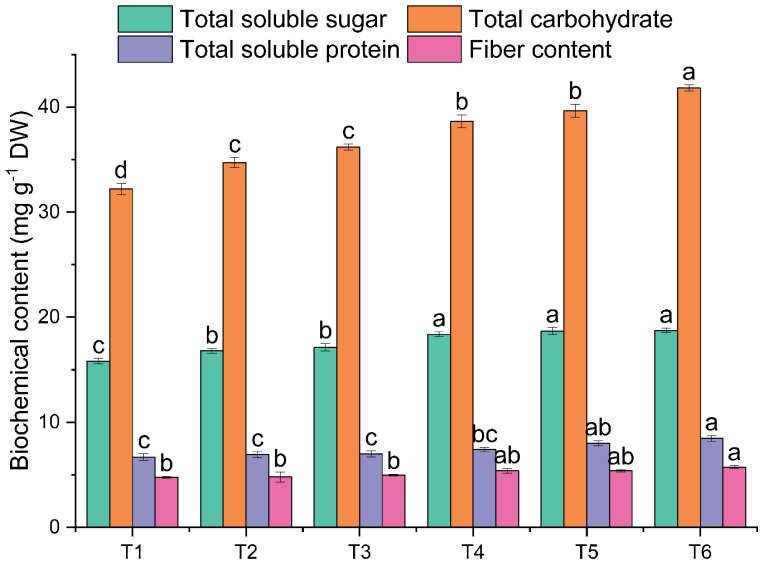

Fig. 5. Effect of integrated application of enriched compost and chemical fertilizers on biochemical characteristics of cucumber. Data presented as the mean of three replicates. Bars sharing the same letter(s) do not differ significantly at 5% probability level ($p \leq 0.05$). T_1: control; T_2: Urea + DAP + SOP; T_3: Zabardast urea + DAP + SOP; T_4: Zn enriched compost; T_5: Zn enriched compost + Urea + DAP + SOP; T_6: enriched compost + Zabardast urea + DAP + SOP.

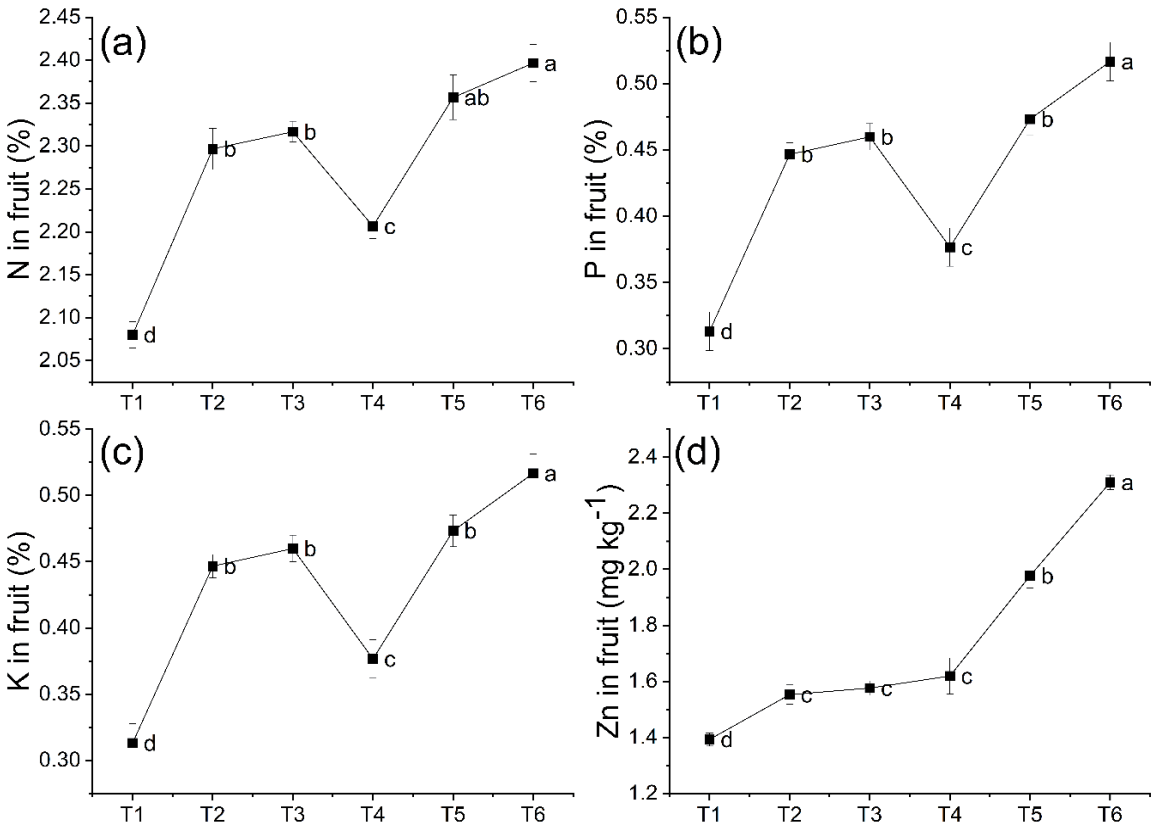

Fig. 6. Effect of integrated application of enriched compost and chemical fertilizers on mineral nutrient contents in cucumber seed. Data presented as the mean of three replicates. Points sharing the same letter(s) do not differ significantly at a 5% probability level ($p \leq 0.05$). (a): nitrogen content in fruit; (b): phosphorous content in fruit; (c): potassium content in fruit; (d): Zn content in fruit; T_1: control; T_2: Urea + DAP + SOP; T_3: Zabardast urea + DAP + SOP; T_4: Zn enriched compost; T_5: Zn enriched compost + Urea + DAP + SOP; T_6: enriched compost + Zabardast urea + DAP + SOP.

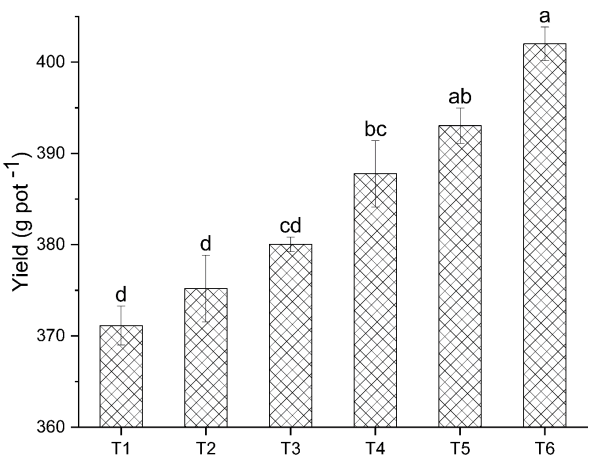

Fig. 7. Effect of integrated application of enriched compost and chemical fertilizers on cucumber yield. Data presented as the mean of three replicates. Bars sharing the same letter(s) do not differ significantly at a 5% probability level ($p \leq 0.05$). T_1: control; T_2: Urea + DAP + SOP; T_3: Zabardast urea + DAP + SOP; T_4: Zn enriched compost; T_5: Zn enriched compost + Urea + DAP + SOP; T_6: enriched compost + Zabardast urea + DAP + SOP.

Impact of Enriched Compost and Different Chemical Fertilizers on Mineral Nutrient Contents in Cucumber Seed

The nutrient content of seeds, including nitrogen (N), phosphorus (P), potassium (K), and zinc (Zn), was significantly influenced by the applied treatments (Fig. 6). Among the treatments, the highest nitrogen content (2.39667%) was recorded in T6 (enriched compost + Zabardast urea + DAP + SOP), followed by T5 (Zn-enriched compost + Urea + DAP + SOP) with 2.35667%, while T1 (absolute control) exhibited the lowest nitrogen content (2.08%). Similarly, phosphorus content was highest in T6 (0.52%) and lowest in T1 (0.31%). Potassium content also varied across treatments, with T6 showing the highest value (3.01%) and T1 the lowest (2.76%). The zinc concentration in seeds significantly increased with the application of zinc-enriched compost. The highest zinc content (39 mg/kg) was observed in T6, followed by T5 (35.33 mg/kg) and T4 (29.33 mg/kg). In contrast, the lowest zinc content (22.83 mg/kg) was found in T1. Overall, the integration of Zn-enriched compost and the use of enriched urea formulations, particularly in T6, significantly enhanced the nutrient profile of seeds compared to other treatments, indicating the synergistic effects of these amendments.

Impact of Enriched Compost and Different Chemical Fertilizers on Cucumber Yield

The crop yield varied significantly under different treatments, indicating the impact of nutrient management practices (Fig. 7). The lowest yield was observed in the absolute control treatment (T1), which produced an average yield of 371.13 units. A slightly higher yield was recorded in T2, which comprised the application of urea, DAP, and SOP, resulting in 375.2 units. Zabardast urea, with DAP and SOP in T3, further increased the yield to 380.03 units. A notable improvement in yield was observed with the application of Zn-enriched compost (T4), which achieved 387.77 units. Combining Zn-enriched compost with urea, DAP, and SOP in T5 further enhanced the yield to 393.03 units. The highest yield, 402 units, was achieved in T6, where enriched compost was used with Zabardast urea, DAP, and SOP. These results highlight the effectiveness of integrating enriched compost and advanced fertilizers like Zabardast urea for maximizing crop productivity.

Correlation Analysis

The Pearson correlation analysis for the dataset highlights significant relationships among the variables (Fig. 8). Organic matter (OM) exhibited a strong positive correlation with soil-Zn (r = 0.89676), vine length (r = 0.86269), vine girth (r = 0.80724), 100-seed weight (r = 0.82111), seed-K (r = 0.73028), and yield (r = 0.80564), indicating its critical role in plant growth and productivity. Soil-N showed strong correlations with seed-N (r = 0.98276) and seed-P (r = 0.97553), as well as high correlations with soil-P (r = 0.88629) and seed-K (r = 0.89444), emphasizing the interdependence of nitrogen availability with other nutrients. Soil-P and soil-K were strongly correlated with each other (r = 0.95998), reflecting their complementary role in soil fertility; their correlations with productivity metrics such as yield were moderate (r = 0.4843 and r = 0.33152, respectively). Soil-Zn demonstrated strong correlations with several productivity-related variables, including seed-K (r = 0.91282), vine length (r = 0.97769), vine girth (r = 0.92949), and yield (r = 0.95263). Seed-N and seed-P were also highly interrelated (r = 0.9939) and showed strong relationships with productivity variables, including yield (r = 0.7207 and r = 0.6984, respectively). Seed-K and seed-Zn showed extremely high correlations with vine length (r = 0.96963 and r = 0.97668), vine girth (r = 0.98911 and r = 0.96247), and 100-seed weight (r = 0.98953 and r = 0.97804), further emphasizing the importance of potassium and zinc in seed and plant development. Among plant growth parameters, vine length and vine girth exhibited very high correlations with yield (r = 0.99322 and r = 0.98704), 100-seed weight (r = 0.99235 and r = 0.99652), and fruit diameter (r = 0.98688 and r = 0.99148), showcasing their strong influence on productivity. Yield was also strongly linked with fruit length (r = 0.90681) and fruit diameter (r = 0.99033), suggesting that fruit characteristics directly impact overall yield. The correlation analysis underscores the complex interplay between soil properties, seed nutrients, and plant growth parameters, highlighting the importance of organic matter, soil zinc, and plant nutrient content for optimizing yield and productivity.

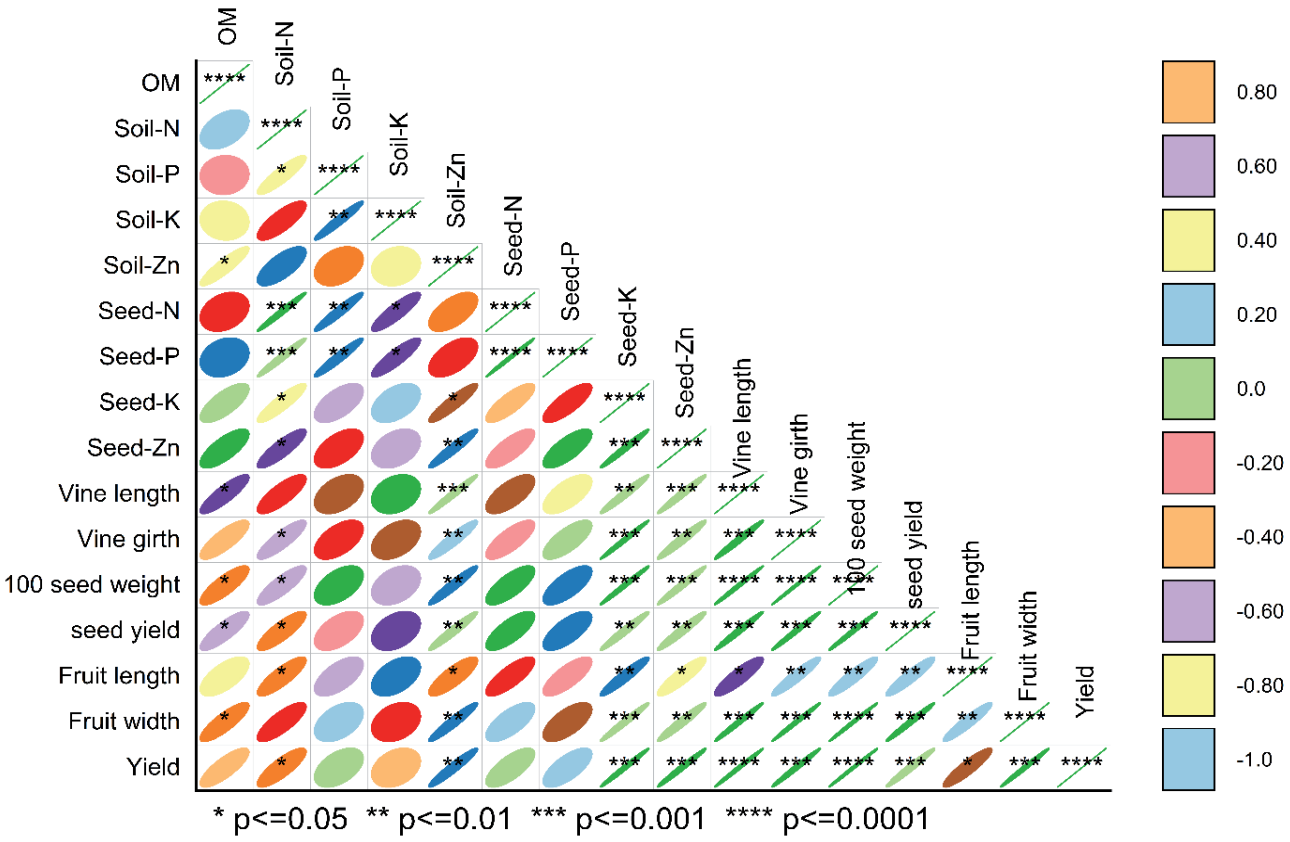

Fig. 8. Pearson's correlation analysis showed the relationship between the studied parameters.

Discussion

The results demonstrate that the integrated application of enriched compost and chemical fertilizers (Particularly in T6 treatment) significantly enhances seed germination, seedling growth, and chlorophyll content, as reflected in key parameters such as SPAD value, seed germination percentage, and seed vigor indices. These improvements were statistically significant ($p < 0.05$), indicating a robust impact of integrated nutrient management on early plant development. Treatments with integrated nutrient management, particularly T6 (enriched compost + Zabardast urea + DAP + SOP), yielded the best outcomes across all measured parameters. This superior performance reflects the synergistic effect of combining organic matter with readily available nutrients from chemical fertilizers, enhancing nutrient uptake efficiency and seed metabolic activity. These findings align with previous literature suggesting that the co-application of organic and chemical fertilizers improves seed vigor and germination [36, 37]. Specifically, T6 produced the highest SPAD value, seed germination, and vigor indices, underlining the positive role of enriched compost in improving soil fertility and promoting seedling growth. This improvement is likely due to the balanced nutrient supply from enriched compost and the inorganic fertilizers, which provide essential macro- and micronutrients, fostering optimal seedling development [38, 39]. The results also suggest that treatments incorporating zinc-enriched compost (T4 and T5) further enhanced seedling growth, supporting the concept that micronutrient supplementation has a significant impact on seed performance [40].

Further supporting the significance of integrated treatments, growth parameters such as vine length, girth, number of leaves, and fruit yield were significantly enhanced, with T6 again exhibiting the highest performance across all traits. This observation is consistent with previous research that highlighted the positive impact of combining organic fertilizers with chemical fertilizers on crop growth and yield [41, 42]. Treatments with Zn-enriched compost, such as T5 and T6, particularly boosted fruit yield, vine girth, and other growth parameters, which aligns with studies showing the crucial role of zinc in plant development, especially concerning nutrient efficiency [43]. Moreover, the inclusion of Zabardast urea in T3 and T6 treatments contributed to larger fruit dimensions and higher seed yield, suggesting the beneficial effects of advanced urea formulations in supplying nutrients for optimal growth [44]. The strong positive correlations observed between vine girth, fruit size, and yield further reinforce the importance of these growth parameters in determining the overall productivity of cucumber plants.

The biochemical parameters, including total soluble sugars, carbohydrates, protein, and fiber content, were significantly improved with treatments of enriched

compost and advanced fertilizers, particularly T6. These improvements in nutritional content are consistent with findings from studies on the positive effects of organic amendments on the biochemical composition of crops [45, 46]. Enriched compost provides organic matter and essential micronutrients that enhance the plant's metabolic processes, leading to higher concentrations of soluble sugars, carbohydrates, proteins, and fiber, for overall crop quality and nutritional value. The enhancement in biochemical properties with Zn-enriched compost, especially in T5 and T6, aligns with research suggesting that zinc supplementation can improve protein synthesis and carbohydrate metabolism [47]. These results highlight that enriched compost and chemical fertilizers enhance crop yield and nutritional quality.

The principal component analysis (PCA) results further supported the beneficial impact of enriched compost. PCA revealed strong associations between integrated treatments and improved soil fertility attributes such as organic matter, total nitrogen, phosphorus, potassium, and zinc. T6 treatment was distinctly separated from other treatments, indicating its superior influence on soil nutrient enrichment. The enrichment of organic matter improves microbial activity and soil structure [48, 49], while enhanced zinc and nitrogen levels support vital physiological processes, such as chlorophyll synthesis and protein production [50, 51]. The strong loading values for these variables in PCA confirm that integrated treatments not only improve plant traits but also enhance long-term soil health, supporting the findings that organic amendments can significantly improve soil fertility and structure [52, 53].

The mineral nutrient content in cucumber seeds, including nitrogen, phosphorus, potassium, and zinc, was significantly higher in treatments that incorporated enriched compost, particularly T6. This aligns with studies that have demonstrated the benefits of organic amendments and micronutrient-rich fertilizers in improving the nutrient profile of seeds [54, 55]. The highest nitrogen and phosphorus content observed in T6 indicates the crucial role of integrated nutrient management in enhancing the nutritional composition of crops, which ultimately influences seed quality and vigor. Furthermore, the higher zinc content in seeds from treatments with Zn-enriched compost supports previous research highlighting the importance of zinc in improving seed nutrient content and plant health [56, 57]. The integration of organic and chemical fertilizers, particularly those enriched with zinc, enhances the quality and nutritional value of cucumber seeds, providing a more nutrient-dense crop.

Yield data support the benefit of an integrated application. T6 (enriched compost + Zabardast urea + DAP + SOP) consistently achieved the highest fruit and seed yield. The statistical significance ($p < 0.05$) of yield differences among treatments confirms the reliability of these observations. This result emphasizes the synergistic effects of organic and inorganic nutrient sources in maximizing crop productivity. The integration ensures slow and rapid nutrient release, optimizing nutrient availability throughout growth stages [58]. The positive correlation between nutrient management and yield suggests that the balanced nutrient supply from integrated treatments maximizes plant growth and fruit production, supporting research that emphasizes the role of macronutrients and micronutrients in improving crop yield [59].

The Pearson correlation analysis highlighted several significant relationships between soil and plant parameters, particularly organic matter, zinc, nitrogen, and yield. The strong correlations between organic matter and various growth and productivity variables suggest its essential role in enhancing plant performance [60, 61]. Furthermore, the high correlation between seed and soil nutrients, particularly nitrogen, phosphorus, and potassium, emphasizes the importance of nutrient availability for optimizing plant growth and productivity. These correlations support the complex interplay between soil health, nutrient availability, and plant growth, highlighting the effectiveness of integrated nutrient management in enhancing overall crop performance. The integrated application of enriched compost and chemical fertilizers, especially the T6 treatment, significantly improved cucumber seed performance, plant growth, soil fertility, biochemical attributes, and yield. These findings highlight the importance of adopting integrated nutrient management strategies for sustainable crop production, with T6 serving as a practical model for balancing yield enhancement and soil health conservation.

Conclusions

The present study introduced a novel concept of combining zinc-enriched compost with advanced chemical fertilizers (Zabardast Urea, DAP, and SOP) as an innovative strategy for integrated nutrient management in cucumber cultivation. This integrated approach significantly improved seed germination, seedling vigor, plant growth, biochemical composition, and yield performance of cucumber. Specifically, the T6 treatment (enriched compost + Zabardast urea + DAP + SOP) consistently demonstrated superior performance across all measured parameters, including chlorophyll content, soluble sugars, total carbohydrates, proteins, and fiber content. In comparison with findings from previous studies, our results align with those reporting that integrated nutrient sources improve nutrient availability, uptake, and crop productivity. However, this study further demonstrates enhanced zinc bioavailability and biochemical quality, a finding not commonly addressed in earlier research. Moreover, the observed positive correlations among soil nutrients, plant growth parameters, and yield components confirm the synergistic interaction of organic and inorganic

inputs, reinforcing the importance of a balanced nutrient supply. The integration of bioactivated enriched compost with chemical fertilizers represents a sustainable and innovative solution for improving soil fertility and cucumber productivity. These findings contribute to a broader understanding of nutrient synergy in sustainable agriculture and highlight the potential of enriched compost-based strategies to enhance crop yield and quality while preserving long-term soil health.

Acknowledgments

The authors extend their gratitude to the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia, for supporting this research through grant number (KFU251738). The authors sincerely acknowledge the Department of Soil Science, the Islamia University of Bahawalpur, for providing facilities for the conduct of this research.

Conflict of Interest

The authors declare no conflict of interest.

References

1. ASHAOLU T.J., REALE A. A holistic review on Euro-Asian lactic acid bacteria fermented cereals and vegetables. Microorganisms, **8** (8), 1176, **2020**.
2. MALLICK P.K. Evaluating potential importance of cucumber (Cucumis sativus L.-Cucurbitaceae): a brief review. International Journal of Applied Sciences and Biotechnology, **10** (1), 12, **2022**.
3. KHAN S.T., MALIK A., ALWARTHAN A., SHAIK M.R. The enormity of the zinc deficiency problem and available solutions; an overview. Arabian Journal of Chemistry, **15** (3), 103668, **2022**.
4. SELIM M.M. Introduction to the integrated nutrient management strategies and their contribution to yield and soil properties. International Journal of Agronomy, **2020** (1), 2821678, **2020**.
5. VASUDHEVAN P., SHUHAO L., RUOYU Z., MANIKANDAN V., YU D., DEVANESAN S., SARANGI P.K., MA H., DIXIT S., PU S. Organic ligand-assisted Fe (II)-activated persulfate for enhanced degradation of chlorinated aromatic contaminants in soil remediation. Journal of Environmental Chemical Engineering, **13** (1), 115237, **2025**.
6. AKHTAR P., AHMAD I., JAMEELA A., ASHFAQUE M., BEGUM Z. Energizing effectiveness of cucumber (Khayarain) for health. A review article. Journal of Emerging Technologies and Innovative Research, **7** (11), 906, **2020**.
7. ALI M. Cluster development-based agriculture transformation plan vision-2025. Project, **131**, 434, **2020**.
8. AHMED N., ZHANG B., DENG L., BOZDAR B., LI J., CHACHAR S., CHACHAR Z., JAHAN I., TALPUR A., GISHKORI M.S. Advancing horizons in vegetable cultivation: a journey from ageold practices to high-tech greenhouse cultivation – a review. Frontiers in Plant Science, **15**, 1357153, **2024**.
9. ADEYEYE S.A.O., ASHAOLU T.J., BOLAJI O.T., ABEGUNDE T.A., OMOYAJOWO A.O. Africa and the Nexus of poverty, malnutrition and diseases. Critical Reviews in Food Science and Nutrition, **63** (5), 641, **2023**.
10. KIANI A.K., DHULI K., DONATO K., AQUILANTI B., VELLUTI V., MATERA G., IACONELLI A., CONNELLY S.T., BELLINATO F., GISONDI P. Main nutritional deficiencies. Journal of Preventive Medicine and Hygiene, **63** (2 Suppl 3), E93, **2022**.
11. GUPTA S., BRAZIER A., LOWE N.M. Zinc deficiency in low-and middle-income countries: prevalence and approaches for mitigation. Journal of Human Nutrition and Dietetics, **33** (5), 624, **2020**.
12. HAGMEYER S., HADERSPECK J.C., GRABRUCKER A.M. Behavioral impairments in animal models for zinc deficiency. Frontiers in Behavioral Neuroscience, **8**, 443, **2015**.
13. ALLOWAY B.J. Soil factors associated with zinc deficiency in crops and humans. Environmental Geochemistry and Health, **31** (5), 537, **2009**.
14. MOSSA A.-W., GASHU D., BROADLEY M.R., DUNHAM S.J., MCGRATH S.P., BAILEY E.H., YOUNG S.D. The effect of soil properties on zinc lability and solubility in soils of Ethiopia–an isotopic dilution study. Soil, **7** (1), 255, **2021**.
15. PRAHARAJ S., SKALICKY M., MAITRA S., BHADRA P., SHANKAR T., BRESTIC M., HEJNAK V., VACHOVA P., HOSSAIN A. Zinc biofortification in food crops could alleviate the zinc malnutrition in human health. Molecules, **26** (12), 3509, **2021**.
16. YADAV A.K., SETH A., KUMAR V., DATTA A. Agronomic biofortification of wheat through proper fertilizer management to alleviate zinc malnutrition: A review. Communications in Soil Science and Plant Analysis, **54** (2), 154, **2023**.
17. MEHMOOD S., AHMED W., RIZWAN M., BUNDSCHUH J., ELNAHAL A.S., LI W. Green synthesized zinc oxide nanoparticles for removal of carbamazepine in water and soil systems. Separation and Purification Technology, **334**, 125988, **2024**.
18. HAMZAH SALEEM M., USMAN K., RIZWAN M., AL JABRI H., ALSAFRAN M. Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. Frontiers in Plant Science, **13**, 1033092, **2022**.
19. MEHMOOD S., OU W., AHMED W., BUNDSCHUH J., RIZWAN M., MAHMOOD M., SULTAN H., ALATALO J.M., ELNAHAL A.S., LIU W. ZnO nanoparticles mediated by Azadirachta indica as nano fertilizer: Improvement in physiological and biochemical indices of Zea mays grown in Cr-contaminated soil. Environmental Pollution, **339**, 122755, **2023**.
20. BÁKONYI N. Examination of Zn deficiency on some physiological parameters in case of maize and cucumber seedlings. Acta Agraria Debreceniensis, (I), 5, **2010**.
21. GARG M., SHARMA N., SHARMA S., KAPOOR P., KUMAR A., CHUNDURI V., ARORA P. Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. Frontiers in Nutrition, **5**, 12, **2018**.
22. DE CORATO U. Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health: A review under the

perspective of a circular economy. Science of the Total Environment, **738**, 139840, **2020**.
23. LIN J., CHENG Q., KUMAR A., ZHANG W., YU Z., HUI D., ZHANG C., SHAN S. Effect of degradable microplastics, biochar and their coexistence on soil organic matter decomposition: A critical review. TrAC Trends in Analytical Chemistry, **183**, 118082, **2025**.
24. PAHALVI H.N., RAFIYA L., RASHID S., NISAR B., KAMILI A.N. Chemical fertilizers and their impact on soil health. Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs, 1, **2021**.
25. NASEEM S., HUSSAIN A., IQBAL Z., MUSTAFA A., MUMTAZ M.Z., MANZOOR A., JAMIL M., AHMAD M. Exopolysaccharide and Siderophore Production Ability of Zn Solubilizing Bacterial Strains Improve Growth, Physiology and Antioxidant Status of Maize and Wheat. Polish Journal of Environmental Studies, **31** (2), **2022**.
26. GRYBOS M., DAVRANCHE M., GRUAU G., PETITJEAN P., PÉDROT M. Increasing pH drives organic matter solubilization from wetland soils under reducing conditions. Geoderma, **154** (1-2), 13, **2009**.
27. ESTEFAN G., SOMMER R., RYAN J. Methods of soil, plant, and water analysis. A Manual for the West Asia and North Africa Region, **3** (2), 65, **2013**.
28. RYAN J., ESTEFAN G., RASHID A. Soil and plant analysis laboratory manual. ICARDA, **2001**.
29. MOODIE C., SMITH H., MCCREERY R. Laboratory Manual for Soil Fertility, pp: 31-9 (Mimeographed). Washington State College, WA, USA. **1959**.
30. DUNN B.L., SINGH H., PAYTON M., KINCHELOE S. Effects of nitrogen, phosphorus, and potassium on SPAD-502 and atLEAF sensor readings of Salvia. Journal of Plant Nutrition, **41** (13), 1674, **2018**.
31. ALBALASMEH A.A., BERHE A.A., GHEZZEHEI T.A. A new method for rapid determination of carbohydrate and total carbon concentrations using UV spectrophotometry. Carbohydrate Polymers, **97** (2), 253, **2013**.
32. MCCLEARY B.V. Importance of enzyme purity and activity in the measurement of total dietary fiber and dietary fiber components. Journal of AOAC International, **83** (4), 997, **2000**.
33. DE BORBA V.S., LEMOS A.C., RODRIGUES M.H.P., GROPELLI V.M., CERQUEIRA M.B.R., BADIALE-FURLONG E. Miniaturization of spectrophotometric methods to determine reducing sugars, total starch and soluble proteins in wheat-based products. Food Analytical Methods, **15** (10), 2756, **2022**.
34. PALACIO-MARQUEZ A., OJEDA-BARRIOS D., JIMENEZ-CASTRO J., PRECIADO-RANGEL P., HERNANDEZ-RODRIGUEZ O.A., SANCHEZ E. Biofortification potential in common bean (Phaseolus vulgaris L.): bioactive compounds, antioxidant capacity and physicochemical properties of 155 varieties grown in México. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, **49** (1), 12123, **2021**.
35. RANGASAMY E., MUTHU V.L., DHANABALAN K., MUNIYANDI M. Determination of proximate composition on some edible crabs with special reference to nutritional aspects collected from coastal waters of Rameshwaram, Tamil Nadu. Food Chemistry Advances, **4**, 100686, **2024**.
36. BHARATHKUMAR S., PRASANTH P., SREENIVAS M., GOUTHAMI P., SATHISH G., JNANESHA A., KUMAR S.R., GOPAL S.V., SRAVYA K., KUMAR A. Unveiling the influence of NPK, organic fertilizers, and plant growth enhancers on China aster (*Callistephus chinensis* L.) CV.'Arka Kamini'seed yield. Industrial Crops and Products, **227**, 120778, **2025**.
37. QIU S., YANG H., ZHANG S., HUANG S., ZHAO S., XU X., HE P., ZHOU W., ZHAO Y., YAN N. Carbon storage in an arable soil combining field measurements, aggregate turnover modeling and climate scenarios. Catena, **220**, 106708, **2023**.
38. IQBAL M.A., RAZA R.Z., ZAFAR M., ALI O.M., AHMED R., RAHIM J., IJAZ R., AHMAD Z., BETHUNE B.J. Integrated fertilizers synergistically bolster temperate soybean growth, yield, and oil content. Sustainability, **14** (4), 2433, **2022**.
39. ANTWI R.A., CHAPPELL C., TWUMASI Y.A., ANNING D.K., OPPONG J., ANNAN J.B., AHOMA G., ATAYI J., FERCHAUD V. Fertility and management strategies of soils in rural and urban forest ecosystems: a review of selected rural and urban forests in Ghana and USA. Geology, Ecology, and Landscapes, 1, **2024**.
40. CHEN F.-B., FENG Y.-C., HUO S.-P. Seed coating with micronutrients improves germination, growth, yield and microelement nutrients of maize (Zea mays L.). Biotechnic & Histochemistry, **98** (4), 230, **2023**.
41. OYETUNJI O., BOLAN N., HANCOCK G. A comprehensive review on enhancing nutrient use efficiency and productivity of broadacre (arable) crops with the combined utilization of compost and fertilizers. Journal of Environmental Management, **317**, 115395, **2022**.
42. MEHMOOD S., AHMED W., MAHMOOD M., RIZWAN M.S., ASGHAR R.M.A., ALATALO J.M., IMTIAZ M., AKMAL M., ABDELRAHMAN H., MA J. Aquaculture sediments amended with biochar improved soil health and plant growth in a degraded soil. Marine Pollution Bulletin, **191**, 114899, **2023**.
43. ZULFIQAR U., HUSSAIN S., MAQSOOD M., ISHFAQ M., ALI N. Zinc nutrition to enhance rice productivity, zinc use efficiency, and grain biofortification under different production systems. Crop Science, **61** (1), 739, **2021**.
44. SWIFY S., MAŽEIKA R., BALTRUSAITIS J., DRAPANAUSKAITĖ D., BARČAUSKAITĖ K. Modified urea fertilizers and their effects on improving nitrogen use efficiency (NUE). Sustainability, **16** (1), 188, **2023**.
45. LAMLOM S.F., IRSHAD A., MOSA W.F. The biological and biochemical composition of wheat (Triticum aestivum) as affected by the bio and organic fertilizers. BMC Plant Biology, **23** (1), 111, **2023**.
46. ZHAO M., ZOU G., LI Y., PAN B., WANG X., ZHANG J., XU L., LI C., CHEN Y. Biodegradable microplastics coupled with biochar enhance Cd chelation and reduce Cd accumulation in Chinese cabbage. Biochar, **7** (1), 31, **2025**.
47. DUAN M., LI T., LIU B., YIN S., ZANG J., LV C., ZHAO G., ZHANG T. Zinc nutrition and dietary zinc supplements. Critical Reviews in Food Science and Nutrition, **63** (9), 1277, **2023**.
48. SINGH N., SACHAN K., BP M., PANOTRA N., KATIYAR D. Building soil health and fertility through organic amendments and practices: a review. Asian Journal of Soil Science and Plant Nutrition, **10** (1), 175, **2024**.
49. MEHMOOD S., MAHMOOD M., NÚÑEZ-DELGADO A., ALATALO J.M., ELRYS A.S., RIZWAN M., WENG J., LI W., AHMED W. A green method for removing chromium (VI) from aqueous systems using novel silicon nanoparticles: Adsorption and interaction mechanisms. Environmental Research, **213**, 113614, **2022**.

50. SETHI G., BEHERA K.K., SAYYED R., ADARSH V., SIPRA B., SINGH L., ALAMRO A.A., BEHERA M. Enhancing soil health and crop productivity: the role of zinc-solubilizing bacteria in sustainable agriculture. Plant Growth Regulation, 1, **2025**.
51. LU D., OU J., QIAN J., XU C., WANG H. Prediction of non-equilibrium transport of nitrate nitrogen from unsaturated soil to saturated aquifer in a watershed: Insights for groundwater quality and pollution risk assessment. Journal of Contaminant Hydrology, 104649, **2025**.
52. XIAO M., JIANG S., LI J., LI W., FU P., LIU G., CHEN J. Synergistic effects of bio-organic fertilizer and different soil amendments on salt reduction, soil fertility, and yield enhancement in salt-affected coastal soils. Soil and Tillage Research, **248**, 106433, **2025**.
53. GONG H., YIN Y., CHEN Z., ZHANG Q., TIAN X., WANG Z., WANG Y., CUI Z. A dynamic optimization of soil phosphorus status approach could reduce phosphorus fertilizer use by half in China. Nature Communications, **16** (1), 976, **2025**.
54. AMANDA BANDARA R., DISSANAYAKA D. Agronomic biofortification of vegetables to achieve iron and zinc nutritional security in food systems. Journal of Plant Nutrition, **48** (6), 974, **2025**.
55. ZHU J., FEI X., YIN K. Assessment of waste-to-energy conversion technologies for biomass waste under different shared socioeconomic pathways. Energy & Environmental Sustainability, **1** (2), 100021, **2025**.
56. ASHENAFI M., DEBASU T., ALEMU D., LEMMA E., BELETE A., AWGCHEW H. Evaluation of Nutrient Role on Quality, Seed Produce, and Yield Constituents of Linseed (Linum usitatissimum L.) Through Nutrient Omission, Central Highland of Ethiopia. International Journal of Agronomy, **2025** (1), 2594741, **2025**.
57. YU D., PENG H., YU C., JI W., WANG X., PU S. Freezing-Induced Redistribution of Fe (II) Species within Clay Minerals for Nonlinear Variations in Hydroxyl Radical Yield and Contaminant Degradation. Journal of Earth Science, 1, **2025**.
58. WANG J., YANG X., HUANG S., WU L., CAI Z., XU M. Long-term combined application of organic and inorganic fertilizers increases crop yield sustainability by improving soil fertility in maize–wheat cropping systems. Journal of Integrative Agriculture, **24** (1), 290, **2025**.
59. REDDY M.P., SEN A., SWAMY C.T., CHELLADURAI P., SIVADURGA K., PANDEY A., SRIVASTAVA R., KAUR A., PUREWAL S.S. Chemistry of Macro-and Micronutrients. Colored Cereals: Properties, Processing, Health Benefits, and Industrial Uses, 96, **2025**.
60. PICCOLO A., DROSOS M. The essential role of humified organic matter in preserving soil health. Chemical and Biological Technologies in Agriculture, **12** (1), 21, **2025**.
61. IAMSOMBOON N., JOTAWORN S., LAMPROM W., BHUMKITTIPICH P., SIRAMANEERAT I. Wastewater Management and Application to Compost for Urban Farming. Water Conservation and Management, **8** (2), 118-124, **2024**.