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Assessment of Nutrient Uptake and Biomass Yield of Green Manure Crops under Straw Treatments in Sustainable Environment

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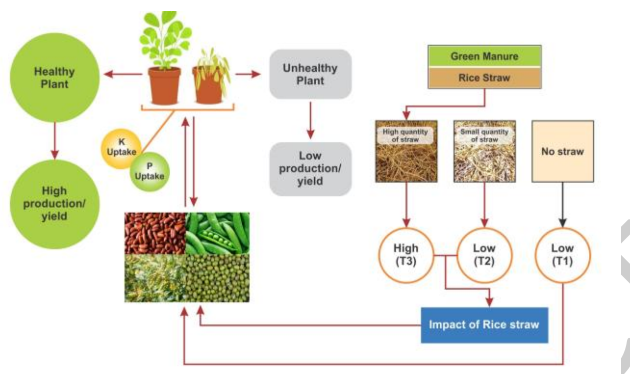
Graphical abstract



Abstract

Rice straw incorporation technique is one of the better alternatives for sustainable agro-industry fertilizers. But its impact on nutrient uptake capacities of green manure crops has still not been studied. This study aimed to investigate the effects of two different rice straw (RS) treatments on various green manure peas *(Pisum sativum* L.), chickpea (*Cicer arietinum* L.), cowpea (*Vigna unguiculata*), alfalfa (*Medicago sativa*), and ryegrass (*Lolium multiflorum*) varieties. Further investigate the biomass yield and nutrient use efficiency. The rice straw treatment is as follows: (T1) no straw incorporation, (T2) RS incorporation at an amount of 3750 kg ha^{-1}, and (T3) RS incorporation at an amount of 7500 kg ha^{-1}. Compared to the no straw treatment, peas showed the highest dry shoot and root biomass production by 79.5% and 87.3%, respectively, on the T3 treatment. While the greatest shoot P uptake abilities were recorded in peas at 127.7%, and chickpeas were 51.8% under the T3 compared to T1 treatment. Green manure species improved K accumulation capacities under rice straw treatments compared to the control. The plant's shoot and root nutrients (N, P, and K) uptake capacities showed a significant positive relationship with soil properties. It is concluded that rice straw treatment (particularly in the amount of 7500kg ha^{-1}) is an effective practice for enhancing nutrient uptake capacities in green manure crops and developing soil fertility status.

Keywords: rice straw; green manures; soil nutrients; biomass production; arid soils.

1. Introduction

It is expected that the world's population will increase by 9.7 billion in 2050. Therefore, agricultural methods are also required to significantly develop food production (X. Wang *et al.* 2020). However, high fertilizer efforts have been used to get a better plant yield (X. Yang *et al.* 2024). The overdose of chemical fertilization supplies in Western Europe, China, India, Pakistan, and North America has led to environmental pollution, whereas in Africa and Latin America it causes soil degradation (Noureldin *et al.* 2013). Management of nutrient efficiency is a difficult task for future agriculture, and numerous methods, separately and in combination, have been engaged to achieve its effectiveness (H. S. Saudy and El–Metwally 2019)**.** The lack of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) has become a significant problem in the modern agricultural environment, adversely affecting crop production (S. Qiu *et al.* 2023). Nitrogen plays a role in photosynthesis through various enzymatic reactions and is part of the chlorophyll molecules (Rasool *et al.* 2020). Phosphorus and K are significant nutrients for energy formation, nucleic acid synthesis, photosynthesis processes, respiration, enzyme activation, and other physiological processes (T. Zhang *et al.* 2023). Nitrogen and P are important nutrients that are required for the proper growth and yield of grain legumes (H. Saudy *et al.* 2020)**.** Potassium is an important element for plant photosynthesis and could also help transfer nutrients through the root mechanisms of a plant, which can increase soil K availability's (Jin *et al.* 2020). It is necessary for early root development, boosts leaf size, enhances nodulation, improves flowering and grain yield, and fastens maturity (El-Mageed *et al.* 2022).

Generally, Pakistani soils are alkaline and calcareous due to a high amount of Ca^{2+} and Mg^{2+} in the soil, resulting in insufficient uptake of nutrients by plants (K. A. Solangi *et al.* 2019). It has been observed that 80% of the P fertilizer applied to the soil transforms into an unavailable form, mostly in calcareous soils (Shaaban *et al.* 2023). In other words, nutrient-deficient soils that have low N, P, and K availability can impose significant constraints on plant growth and development (Anwar *et al.* 2025). Utilization of straw incorporation techniques is mostly used as organic fertilizer to increase soil fertility. However, rice straw is an excellent source for sustainable agricultural production due to the presence of vital nutrients and organic material that can improve soil health and crop yield. Short-term straw application induces microorganisms that help to improve N and reduce N mineralization, thereby increasing the net retention grain yield. In this regard, green manure species were grown under straw treatments to improve soil nutrient availability in green manuring practices (Mubarak *et al.* 2021).

Green manure plays a significant role in the nutrient cycle, increases soil organic matter (SOM) and N content through biological N fixation, and can also provide the soil N supply for next year's crops (F. Solangi *et al.* 2019). The plantation of legumes is important for maintaining essential elements and could be used as an alternative source of nutrients (Stagnari *et al.* 2017). Chickpeas and cowpeas are crucial nutritional legume pulses; they are a vital resource of low-cost, high protein content next to cereal grains (Jukanti *et al.* 2012). Green peas belong to the Fabaceae family; these crops have the ability to fix N in the soil. Peas are an essential winter vegetable crop in Pakistan due to their nutritional capacity. Alfalfa and ryegrass are fodder crops that have high nutrition amounts and are broadly cultivated throughout the world. Green manure crops enhance N, P, and K availability due to a number of mechanisms by which they can survive in nutrients stress environmental conditions. For example, by releasing organic acids from their roots, which could solubilize stable P, and secreting phosphatase enzymes to convert organic P into the inorganic P compounds (Du *et al.* 2024).

Compared to non-leguminous plants, legume crops have higher P requirements for optimal N fixation, as P plays a vital role in energy conversion in nodules. Previously, (Moll *et al.* 1982) defined nutrient use efficiency as the yield of grain/unit of nutrient supplied. Similarly, some researchers (Hammond *et al.* 2009) defined P uptake efficiency (PUpE) as referring to the capacity of plants to uptake P from the soil and the P use capacity (PUtE) of P absorption and use by a plant for biomass yield. Improving phosphorus use efficiency (PUE) could be dependent on higher P absorption abilities and optimizing its utilization (Martinez-Feria *et al.* 2018). Improving nutrient uptake efficiency by legumes requires better availability of nutrients from the soil, which is used to accelerate biomass growth and distribution to the above-ground parts (Schönleber and Ivers-Tiffée 2015). These crops also reduce fertilizer input in the ecosystem due to their biological N fixation (Tsialtas *et al.* 2018). In addition, the application of straw incorporation could supply a higher amount of major nutrients, which is an excellent value for maintaining soil fertility (Tan *et al.* 2017). The practice of straw incorporation has become widespread because it helps improve soil nutrient efficiency and reduce soil erosion and water loss, thus contributing to the basic practices that promote sustainable agricultural systems (X.-Z. Han *et al.* 2012). In an agricultural environment, straw incorporation practices have been defined as an easy and effective method to enhance soil nutrient utilization efficiency and subsequent crop production (F. Solangi *et al.* 2024). It is also necessary to identify the good sources of organic fertilizer that can be used as fertilizer and their best combination with a suitable portion of inorganic fertilizer for crops.

It is reported that rice straw incorporation practices can increase N (0.5–0.8%), P (0.07–0.12%), K (1.16–1.66%), content, and other elements in soil, thereby improving the efficiency of soil nutrients and increasing crop yields (Lan *et al.* 2012). The incorporation of rice straw directly into the soil can provide favorable environmental conditions (Chivenge *et al.* 2020). The straw-applied practices could be utilized as a natural organic source and as an alternative to synthetic fertilizers (X. Wang *et al.* 2015). The crop straw is the main source of organic matter, which provides nutrients to soils that could improve biological properties activities (P. Zhang *et al.* 2016). Therefore, the changes in soil properties under both short and long-term applications of straw are valuable to soil microbes because they have a significant influence on nutrient cycling, microbial activity, and overall soil (Li *et al.* 2022). Long-term crop cultivation reduces soil fertility by incorporating crop straw that has decomposed into the soil, while this decomposing process provides nutrient to the plant (Gaind and Nain 2007). Further, long-term trials, straw incorporation practices are mainly used to improve the wheat yield quality and are mainly incorporated in paddy fields. Furthermore, many studies emphasize rice straw incorporation practices to improve soil organic carbon and carbon nitrogen ratios through different practices in the soil, including the direct application of straw and incorporation with tillage at various soil depths (X. Han *et al.* 2018; Yao *et al.* 2015), and various amounts of straw incorporated with high amounts of N chemical fertilizer (S.-J. Qiu *et al.* 2012). The limited literature available on the cultivation of green manure crops under straw treatments to improve plant macronutrients uptake abilities and soil nutrient contents. Part of the current research focuses on the response of green manure to the transformation of nutrients into above-ground plant parts under straw treatments. We hypothesize that the rice straw incorporation practice could affect the ability of green manure species to take in nutrients. Keeping this opinion in mind, the present research was shown to study the effect of in situ incorporations of rice straw treatments on different species of green manure crop biomass production and nutrient uptake. The important objectives of the present research are (1) to investigate the effects of two different RS treatments on the nutrient (N, P, and K) uptake capacities of green manure varieties, and the highest PUE among different varieties was further investigated; and (2) to explore soil nutrient availabilities and their interaction with plants nutrient absorption capacities.

2. Materials and Methods

A greenhouse experiment was conducted in Sindh province, situated in southern Pakistan, longitude 25°42′34′′ N and latitude 68°54′08′′ E. The experiment was planned in a completely randomized design with two factors: rice straw treatment and different species. The rice straw of the super basmati variety (*Oryza sativa*) was used in this experiment. The rice straw was cut into 15-cm pieces for use after drying at 70°C and then manually mixed with dry soil at different levels. The applied straw amount and fertilizer rate are shown in **Table 1**. Experimental soil was properly homogenized with 100 mg/kg P (P_2O_5) and K (K_2O) fertilizers with each rice straw treatment, and every treatment has four replicates. After that, 50% water was added to maintain water holding capacity (WHC) in every pot. The applied fertilizers were treated as superphosphate (P_2O_5, 12%) and potassium chloride (K_2O, 60%). The pot experiment soil was collected with a depth of 0–15 cm using an auger, and the initial soil characteristics are as follows: soil organic matter (SOM) was 6.5 g kg^{-1}; total nitrogen (TN) was 1.5 g kg^{-1}; available P was 18.7 mg kg^{-1} and available K was 120.3 mg kg^{-1}; soil pH and EC cmol kg^{-1} were 7.8, and 0.36 respectively. The texture class was clay loam with a bulk density of 1.20 g cm^{-3}. The RS nutritional composition was N, 1.25% P, 0.28% K, and 4.81%. The green manure seeds were soaked in water for 1 day before sowing. After soil preparation, 10 to 12 seeds of each green manure species were sown in pot^{-1}, and covered with dry soil Green manure species such as peas (*Pisum sativum* L.), chickpeas (*Cicer arietinum* L.), cowpea (*Vigna unguiculata*), alfalfa (*Medicago Sativa* L.), and ryegrass (*Lolium multiflorum.*) were followed as species names (peas 2009, DG 92, CP 1, Sarsabz, and Italian ryegrass), respectively, seeded on 5th November 2020. The above mentioned species and experimental soil were collected from the Pulses Research Sub-station, Tandojam city, Sindh province, Pakistan.

Table 1. The rice straw applied amount and chemical fertilizers dose

Treatment	Rice straw	Chemical fertilizers
T1	0 kg ha^{-1}	(P_2O_5), (K_2O) 100 mg/kg
T2	3750 kg ha^{-1}	(P_2O_5), (K_2O) 100 mg/kg
T3	7500 kg ha^{-1}	(P_2O_5), (K_2O) 100 mg/kg

2.1. Plant sampling and analysis

All species were harvested on 20th February 2021. The plant parts (shoots and roots) were separated and weighed, then dried in an oven at 70°C for 2 days, crushed, and stored for nutrient analyses. The N, P, and K concentrations in plant shoot samples were analyzed using a digestion method involving a mixture of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) at high temperatures, followed by an ashing process for nutrient determination. The following methods determined the plant's nutrient contents: plant N was determined by the Kjeldahl digestion method (Aleixo *et al.* 2008), P analysis by the molybdovanadate method (Soon and Kalra 1995), and the flame photometry method was used for K determination. Shoot and root PUpE is examined by the amount at which a plant absorbs a nutrient and the supplied P amount. Shoot and root PUtP calculates the dry biomass per unit of nutrient accumulated in the plant. PUE was estimated as the total amount of nutrients available that the plant utilized. Phosphorus use efficiency percentages is measured by PUpE x PUtP described by (Moll *et al.* 1982).

For shoot and roots PUE, and nutrients N, P, and K uptakes were calculated by following equations.

$$\text{Uptake} = \left[\begin{array}{l}\text{plant uptake contents } (\%) \text{ in dry matter} \times \\ \text{dry biomass yield } \left(\text{g pot}^{-1}\right)\end{array}\right] \Big/ 100 \quad (1)$$

$$\text{P uptake efficiency (PUpE)\%} = (Nt) \;/\; (Ps) \times 100 \quad (2)$$

Where Nt is the amount of P accumulated in the shoot dry matter of a plant at maturity and Ps = P supplied straw + fertilizer.

$$\text{P utilization efficiency (PUtE)\%} = (\text{Nt} \;/\; \text{Shoot dry Biomass} \times 100) \quad (3)$$

Where Nt is nutrients accumulate in the dry matter of a plant at maturity and shoot dry biomass weight at maturity

$$\text{P use efficiency(PUE) \%} = (\text{PUpE}) \,\% \times (\text{PUtE}) \,\% \quad (4)$$

2.2. Soil sampling and determination

However, collected soil samples were divided into two portion, while one portion was quickly kept at -4°C for inorganic N analysis. The second part of samples was dried at room temperature and further passed through a 2-mm sieve for the analysis of soil P, K, and the soil pH range. The sub-samples were passed through a 0.25-mm sieve further to analyze total soil nitrogen and soil organic matter. Drying experimental soil in an oven for two days at 105 °C provided information on its moisture content for inorganic N analysis. Determination of soil inorganic N contents by the Kjeldhal process of steam distillation as described by (Thomas 1996). Soil total nitrogen (TN) content was analyzed by the Kjeldahl method (Nelson and Sommers 2018). SOM was determined by Walkley-black method (Zelazny *et al.* 2018). A pH meter (Jenway, Model-3510, Gransmore Green, Felsted, Dunmow, Essex, CM6 3LB, UK) was used for determining soil pH at a 1:2.5 soil/water ratio. The Olsen P was extracted with 0.5 M $NaHCO_3$ and analyzed using visible light spectroscopy in blue light (UV–VIS spectrophotometer, Model UV-2100, Shimadzu, Kyoto, Japan), following the method in (Murphy and Riley 1962). Soil available potassium was examined through flame photometry using 0.5g of soil and 1M of ammonium acetate (NH4OAc) (Walker and Barber 1962).

2.3. Statistical analyses

One-way ANOVA was used to evaluate the effects of straw incorporation treatments on various types of green manure varieties and soil properties, and SPSS Statistics Version 20.0 (Corp., Armonk, NY, USA) was used for Duncan's multiple values of tests at ($p < 0.05$) measure the treatment differences. The IBM SPSS Statistics Version 20.0 was also used (Corp., Armonk, NY, USA) for correlation analysis. According to Pearson's correlation coefficient analysis, we evaluated the correlation between shoot and root nutrient uptake of green manure varieties and its relationship with soil properties using *, which presented a *p* level at < 0.05, and ** which indicated a *p* range at < 0.01 probability levels.

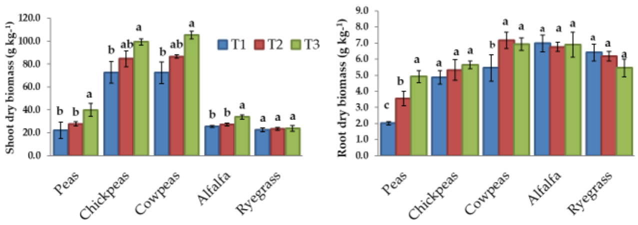


Figure 1. Effects of straw incorporation treatments on shoots and roots dry biomass of green manure crops. Small letters indicate a significant difference at $P < 0.05$, based on Duncan's multiple range test, repeats $n = 4$, mean ± standard error. Note: T1: no straw incorporation; T2: incorporation of rice straw at a rate of 3750 kg ha^{-1}, T3: incorporation of rice straw at a rate of 7500 kg ha^{-1}.

3. Results

3.1. Shoots and roots dry biomass

Significant changes in shoots and root dry biomass of the different green manures including peas, chickpeas, cowpeas, alfalfa, and ryegrass were observed under both RS treatments, T2 and T3, compared to the no straw (control) treatment (**Figure 1**). Peas provided the highest shoot and root biomass by 79.5% and 87.3%, respectively, on the T3 treatment compared to the control. Chickpeas increased shoot dry biomass yield and root dry biomass i.e., 37.5% and 10.9% on T3, which was higher than T1 treatment. Cowpeas produced maximum shoot and root biomass of 45.3% and 48.0% under the T3 treatment than without the straw treatment, respectively. Compared with the control, alfalfa improved shoot dry biomass, i.e., 32.9% on T3 treatment, while ryegrass decreased shoot biomass by 20.7% under the T3 which is lower than T1 treatment.

3.2. Shoot N, P, and K uptakes

The RS treatments significantly ($P < 0.05$) enhanced the shoot N uptake of different green manure species (**Table 2**). Compared with the control, the shoot N uptake capacity of different species such as pea, chickpea, cowpea, alfalfa, and ryegrass, followed by 193.4%, 52.0%, 29.5%, 59.5%, and 14.9%, respectively, was significantly increased on T3 straw treatment. Straw treatments also showed changes in the P and K uptake abilities of various species; the highest shoot P uptake was recorded in peas at 127.7%, and chickpeas were 51.8% on T3 compared to without straw treatment. However, T3 treatment also enhanced P uptake capacities in cowpeas and alfalfa, i.e., 35.4% and 48.4%, respectively, as compared to control. In contrast, ryegrass reduced P uptake ability in T3, which is lower than T1 treatment. While greater K uptake abilities were increased in alfalfa by 356.8% and pea by 289.1%, respectively, in the T3 straw treatment, which was higher than no straw treatments. Peas, chickpeas, and cowpeas significantly improved K uptake abilities under straw treatments.

Table 2. Shoots nutrient uptake (g kg^{-1}) in green manure species under rice straw treatments, repeats $n = 4$, mean ± standard error.

Species	Treatment	Shoots		
		N uptake (g kg⁻¹)	**P uptake (g kg⁻¹)**	**K uptake (g kg⁻¹)**
Peas	T1	0.284±0.073b	0.069±0.003b	0.270±0.020c
	T2	0.926±0.051a	0.101±0.005ab	0.835±0.020b
	T3	1.834.±0.061a	0.158±0.037a	1.049±0.063a
Chickpeas	T1	1.527±0.417a	0.159± 0.039b	1.0491±0.149b
	T2	2.527±0.525a	0.200±0.057b	1.006±0.261ab
	T3	2.513±0.525a	0.241±0.010a	2.352±0.132a
Cowpeas	T1	1.285±0.196b	0.148±0.011a	1.142±0.048c
	T2	1. 848±0.177ab	0.199±0.034a	1.450±0.193b
	T3	1.665±0.111ab	0.200±0.021a	1.721±0.130a
Alfalfa	T1	0.495±0.025b	0.074±0.003a	0.363±0.064b
	T2	0.514±0.027b	0.081±0.008a	0.910±0,058ab
	T3	0.787±0.037a	0.110±0.001a	1.657±0.059a
Ryegrass	T1	0.496±0.030a	0.103±0.016a	0.461±0.029b
	T2	0.570±0.081a	0.070±0.021a	1.150±0.112a
	T3	0.570±0.031a	0.081±0.007a	1.260±0.072a

Note: T1: no straw incorporation, T2: incorporation of rice straw at a rate of 3750 kg ha^{-1}, T3: incorporation of rice straw at a rate of 7500 kg ha^{-1}. The small letter shows significant changes ($p < 0.05$) using Duncan's multiple range tests.

3.3. Roots N, P and K uptake

The RS treatments boost the root N and K absorption capacity while reducing the P uptake amount in the roots of green manure species (**Table 3**). Treatment T3 increased the greatest amounts of root N uptake in peas, chickpeas, and cowpeas, i.e., 181.4% and 32.9%, and

17.3%, respectively, compared to the control. Alfalfa reduced root N uptake ability, which is lower than control. While root P uptake trends decreased in green manure species in the following directions; 38.8%, 24.4%, and 12.5% for peas, ryegrass, and cowpeas on T3 treatment, then no straw incorporation. The higher root K uptake was recorded in peas and alfalfa, i.e., 205.6% and 130.8%, on the T3 treatment which is greater than T1. The lowest K absorption was in cowpea, 54.5%, on T2 which was higher than without straw incorporation.

Table 3. Root nutrients (N, P, and K) uptake (g kg^{-1}) in different legumes under rice straw treatments repeats *n* = 4, mean ± standard error.

Species	Treatment	Roots		
		N uptake (g kg^{-1})	P uptake (g kg^{-1})	K uptake (g kg^{-1})
Peas	T1	0.042±0.004b	0.022±0.001a	0.039±0.003b
	T2	0.084±0.009a	0.019±0.002a	0.118±0.015a
	T3	0.092±0.004a	0.021±0.002a	0.120±0.008a
Chickpeas	T1	0.095±0.013a	0.041± 0.003a	0.094±0.06a
	T2	0.119±0.020a	0.020±0.002a	0.125±0.018a
	T3	0.126±0.009a	0.013±0.001a	0.121±0.03a
Cowpeas	T1	0.143±0.022a	0.046±0.009a	0.099±0.014b
	T2	0.167±0.019a	0.021±0.001a	0.161±0.012a
	T3	0.167±0.009a	0.025±0.001a	0.170±0.011a
Alfalfa	T1	0.145±0.018a	0.029±0.001a	0.137±0.010c
	T2	0.161±0.008a	0.018±0.002a	0.221±0.008b
	T3	0.139±0.004a	0.027±0.001a	0.316±0.019a
Ryegrass	T1	0.129±0.025a	0.029±0.007a	0.144±0.022b
	T2	1.134±0.012a	0.021±0.003a	0.255±0.043a
	T3	0.120±0.016a	0.019±0.001a	0.249±0.024a

Note. T1: no straw incorporation; T2: incorporation of rice straw at a rate of 3750 kg ha^{-1}, T3: incorporation of rice straw at 7500 kg ha^{-1}. The small letters showed significant modifications ($p < 0.05$) using Duncan tests.

Table 4. Shoot and root P uptake effeciency PUpE (%), P utilization efficiency PUtE (**%**), and P use efficiency PUE (%) of different green manure species under straw treatments.

Species	Treatments	Shoots			Roots		
		PUpE (%)	PUtE (%)	PUE (%)	PUpE (%)	PUtE (%)	PUE (%)
Peas	T1	0.564	0.313	0.177	0.101	0.662	0.072
	T2	0.821	0.364	0.299	0.134	0.453	0.061
	T3	1.283	0.395	0.506	0.168	0.412	0.069
Chickpeas	T1	1.291	0.218	0.281	0.104	0.256	0.027
	T2	1.626	0.213	0.347	0.116	0.224	0.022
	T3	1.960	0.225	0.441	0.157	0.252	0.029
Cowpeas	T1	1.203	0.210	0.252	0.157	0.345	0.054
	T2	1.617	0.240	0.389	0.140	0.239	0.033
	T3	1.628	0.276	0.450	0.204	0.363	0.074
Alfalfa	T1	0.602	0.288	0.173	0.166	0.286	0.047
	T2	0.660	0.297	0.196	0.163	0.286	0.048
	T3	0.894	0.324	0.289	0.185	0.296	0.115
Ryegrass	T1	0.837	0.462	0.387	0.248	0.464	0.060
	T2	0.572	0.300	0.172	0.151	0.299	0.045
	T3	0.662	0.350	0.232	0.152	0.344	0.052

Note. T1: no straw incorporation; T2: incorporation of rice straw at a rate of 3750 kg ha^{-1}, T3: incorporation of rice straw at 7500 kg ha^{-1}.

3.4. Effects of rice straw treatments on soil nutrient contents

In general, RS treatments changed the amount of available N, P, and K in the soil after harvesting different types of green manures (**Figure 2**). Compared with the control, the cowpea, pea, and ryegrass increased NO_3^- N content by 26.5%, 45.5%, and 79.8%, respectively, in the T3 straw treatment. Soil TN did not find any significant results under RS treatments. The T3 straw treatment reduced the soil-available P content in peas by 14.6% compared with the control. Soil available P contents decreased in chickpeas and cowpeas by 20.9% and 17.8% under T3 treatment, respectively, which is lower than the control. At the same time, compared to the control, ryegrass and alfalfa decreased soil P, i.e., 21.9% and 46.2% on T3 straw incorporation treatments, respectively. In contrast, straw applied treatments improved the soil's available K content in all different species. The maximum K content noted in alfalfa was lower by 126.2% on T3 compared with the control. While cowpeas improved by 51.7% more soil available K content of available K by 8.6% in ryegrass, which was higher than the no straw incorporation treatment.

Table 5. Pearson correlations (r) between plants shoot N, P, and K uptakes and soil properties.

Parameters	N	P	K	SOM	TN	NH_4^+	NO_3^-	P	K	pH
Shoot N	1	0.312**	0.484**	-0.253	-0.065	0.054	-0.068	0.001	0.336**	-0.294*
Shoot P		1	-0.0378	-0.256*	-0.065	-0.156	-0.075	0.232	0.162	0.505**
Shoot K			1	-0.231	0.364**	0.146	0.381**	0.267*	0.084	0.597**
SOM				1	0.321	0.130	0.364**	-0.460*	0.633**	-0.557**
TN					1	0.207	0.417	-0.516**	0.217	0.522**
NH_4^+						1	0.017	-0.204	0.012	0.183
NO_3^-							1	-0560*	0.248	0.713**
AP								1	-0.299**	-0.655**
AK									1	0.373**
pH										1

SOM; organic matter, TN (total nitrogen), NH_4^+ and NO_3^- (mineral nitrogen), P (phosphorus), K (potassium), and pH (soil pH)

Table 6. Pearson correlation (r) between plants root N, P, and K uptakes and soil properties.

Parameters	N	P	K	SOM	TN	NH_4^+	NO_3^-	P	K	pH
Root N	1	0.522**	0.522**	-0.242	-0.088	0.037	0.057	0.006	0.323	-0.304*
Root P		1	0.454**	-0.257*	-0.205	0.073	-0.393**	0.122	-0.171	-0.402**
Root K			1	0.336*	0.357**	0.156	0.460**	0.224	-0.205	0.590**
SOM				1	0.321	0.130	0.364*	-0.460**	0.633**	0.557**
TN					1	0.207	0.417**	0.516**	0.217	0.522**
NH_4^+						1	0.017	-0.203	0.0122	0.183
NO_3^-							1	-0.560	0.249	0.713**
AP								1	-0.299**	-0.65**
AK									1	0.373**
pH										1

SOM (organic matter), TN (total nitrogen), NH_4^+ and NO_3^- (mineral nitrogen), P (phosphorus), K (potassium), and pH (soil pH).

3.5. Relationship between shoots and roots nutrients and soil properties

Table 5 shows that there are significant relationships between shoot N, P, and K uptake of different green manures and the soil properties. The shoot N uptake showed a significant negative relation with soil K and pH r = -0.336* and -0.294*, respectively. While P uptake was shown to have a negative relationship with SOM (r = -0.256*) and a significantly positively linked with soil pH = 0.505**. Shoot K uptake was significant positive linked with soil TN, NO_3^-, and AP by r = 0.364**, 0.381**, and 0.267**, respectively. Shoot K uptake shows a significant negative relation with soil pH (r = -0.597**).

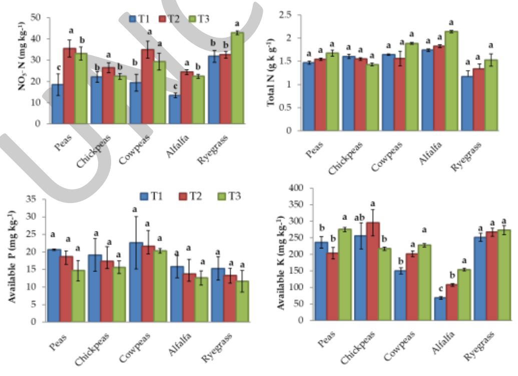


Figure 2. Influence of rice straw treatments on soil (NO_3^-) nitrate nitrogen, total nitrogen, available phosphorus, and available potassium. Different small letters indicate a significant difference at $P < 0.05$, based on Duncan's range test, repeats $n = 4$ mean ± SE. Note. T1: no straw incorporation; T2: incorporation of rice straw at a rate of 3750 kg ha^{-1}, T3: incorporation of rice straw at 7500 kg ha^{-1}.

However, the uptake capacity of roots for N, P, and K was significantly correlated with soil properties (**Table 6**). Legume root N uptake was only significantly negatively related to soil pH (r = -0.304*). Root P uptakes showed a significant negative relation with SOM by r = -0.257*, NO_3^- by r = -0.393**, and soil pH by r = 0.402**. Root K uptake of green manure species positively interacts with soil properties such as SOM, TN, NO_3^-, and soil pH, by r = 0.336*, 0.357**, 0.460**, and 0.590**.

4. Discussion

4.1. Influence of rice straw on green manure biomass and nutrient uptake

The presented data show that the straw incorporation treatment promotes the macronutrients, for example, N, P, and K accumulation abilities of green manure shoots and roots and develops greater biomass production (**Figure 1**). Previous research has demonstrated that straw application not only provides nutrients but also increases biomass yield and grain yield (X. Wang *et al.* 2018). Similarly, the incorporation of straw into the soil can reflect plant biomass and production (Karami *et al.* 2012). A mixture of two fertilizers, including organic and inorganic fertilizers, not only improves N uptake efficiency by plants but also restores N in the soil (Abd–Elrahman *et al.* 2022; Moe *et al.* 2017). Crop straw contains several essential nutrients needed for plant growth and impacts N mineralization and possibly N uptake in crops (Zhao *et al.* 2014). However, the ability of plants to absorb nutrients depends on the ability of the soil to provide sufficient nutrients and the ability of the plant to acquire, transport, and re-migrate to other parts of the plant through the roots and shoots (F. Solangi *et al.* 2024). In addition, the concentration of crucial nutrients increases due to microbe-promoted mineralization, which can increase the available nutrients absorbed by plants (Osman 2013; Salem *et al.*, 2022). A previous study by (Y. Zhang *et al.*, 2018) described that cumulative soil pH due to the application of RS compost might have a favorable effect on overall plant uptake availability. The current study indicates straw treatments enhance legume shoots and root K uptake. Relatively high concentrations of K^+ uptake were found in plants, especially the shoots of all crops (Ashraf, 2004). Even at very low potassium concentrations, the roots of legumes actively absorb large amounts of potassium and transport it from roots to shoots (Z. Zhang *et al.*, 2021).

4.2. Influence of straw treatments on shoot and root PUE of different species

This research demonstrated that the straw incorporation trend enhanced the plant's nutrient uptake capabilities. Moreover, among all species, chickpea showed the highest N uptake on T3 treatments, while greater P and K uptake was observed in T2 (**Table 2**). Similar results were shown in an earlier study that gives support to the current study, where faba beans accumulated high levels of nitrogen in their shoots and roots in comparison with various legumes (Jin *et al.*, 2020). Straw incorporation treatments increase microbes and improve the high N fixation capacity of a legume species, which is reflected in the high N uptake in plants. According to the previous study, based on cluster root analysis, legumes can be classified into different groups. The cluster root system of soybeans, peanuts, chickpeas, and peas might have quick early shoot growth and a high lateral root development, which could help increase nutrient uptake from the soil (H. S. Saudy *et al.*, 2018). The current study shoed the highest shoot and root PUE efficiency recorded in peas among all green manures (**Table 4**). In consideration, efficient and inefficient plants were categorized into two classes based on their biomass response to P availability and the conversion of plant supply nutrients into dry yield (Vose 1987); a plant that provides a high biomass yield under a P-sufficient environment is known as a P-efficient cultivar, and plants that produce a lower yield at low nutrient content are known as P-inefficient cultivars (F. Solangi *et al.* 2023). However, green manure species have unique root morphological characteristics, and root-related traitssignificantly influence PUE (Ozturk *et al.* 2005).

4.3. Effects of rice straw treatments on soil nutrients availability

The straw incorporation application significantly enhanced soil nutrient availability. Straw incorporation seems promising for maintaining and restoring soil fertility (Zhao *et al.* 2019). Present results have shown RS treatments have maximized a small amount of soil N content (**Figure 2**). In addition, using organic and inorganic fertilizers can improve soil physicochemical properties and serve as a source of nutrient management techniques to reduce nitrogen loss and improve soil nitrogen efficiency (Chadwick *et al.* 2015). Crop residues also contain a lot of organic matter, which, when mixed into the soil, can improve soil quality and ultimately contribute to increased crop yields. The RS treatments could reduce available soil P contents under the cultivation of green manure species (**Figure 2**). The current study confirms earlier research that found rice straw incorporation decreased soil availability in the pot experiments. Earlier research (Yan *et al.* 2016) found that rice straw incorporation reduced soil phosphorus availability in pot experiments, which supports with the findings of the current study. This reduction may occur because rice straw treatments enhance microbial biomass and activity, leading to the transformation and retention of inorganic phosphorus in the soil (X. Wang *et al.* 2018). Furthermore, applying straw amounts increases organic matter in the soil's top layer, thereby decreasing the amount of P absorbed by inorganic particles that attach to soil colloids (P. Zhang *et al.* 2016). Similarly, (Yadvinder-Singh *et al.* 2010) reported that field and pot experiments showed that the soil solid phase absorbed most of the P released by rotting straw, but not all of it entered the soil solution. Other previous results demonstrated that straw P retention takes multiple years to reduce soil adsorption of P and improve the available soil P on the soil surface (Gupta *et al.* 2007).

The present experiment shows straw incorporation treatments enhanced soil available K content (**Figure 2**). According to earlier studies described by (Sial *et al.* 2019), which showed that the developed K content of soil at a depth of 0–20 cm as a result of rice straw application and rice straw retention in fields could also release a considerable amount of K to the soil. The changes in soil pH during the decomposition of rice straw could enhance a large amount of soil K (Y. Zhang *et al.* 2018). It is considered that RS treatments might transform a portion of non-exchangeable K into one that is exchangeable and available for plants (H. Y. Wang *et al.* 2011). Organic materials, mainly recycled rice straw, can provide a considerable amount of K and sometimes even more than plant requirements (Singh *et al.* 2018).

4.4. Relationship between legume shoots and roots N, P, and K uptakes and soil properties

Pearson's correlation analysis showed the nutrient uptake capacities of plant shoots and roots were significantly correlated with soil properties. Current data shows a significant negative association among shoot and root N uptake and soil pH. This finding supported our study, which showed short-term applied straw could induce N immobilization by microbe activities due to straw incorporation and decrease N mineralization (Liu *et al.* 2023). Early decomposition of returned straws affects the breakdown of nitrogen-containing substances. In the later stage of straw decomposition, the N is largely consumed by plants, the NH_3^+ produced is greatly reduced, the soil pH is maintained at normal, and the activity of soil microorganism's increases. Straw incorporation could upgrade microbial biomass and N mineralization in the soil (Eagle *et al.* 2000). The present study indicated a relationship between plant nutrient uptake and SOM. Soil organic matter is an important factor in soil quality because of its effects on soil properties. According to a previous study, straw incorporation directly correlates with soil carbon and SOM, which can lead to plant nutrient uptake capacities (Y. Zhang *et al.* 2018). The addition of RS to the soil increases SOM because the decomposition of RS increases the release of dissolvable SOM from the straw, which leads to an increase in potential nutrient availability (Lou *et al.* 2011). Several studies have demonstrated that crop residue incorporation is beneficial for soil fertility and can maintain soil structure and water content (M. Yang *et al.* 2021). Furthermore, another study found that when rice straw is applied to the soil, it results in increased P and K uptake compared to no straw incorporated (Ali *et al.* 2021; Mao *et al.* 2022). The rate of decomposition and the release of nutrients depend on soil type and season, even though nutrients become available for plant uptake after straw decomposition. Similarly, the plant's shoot K uptake abilities indicated a significant negative interaction with pH, and root K uptake has a positive relationship with soil pH (**Tables 5 and 6**). An earlier study proposed that during the process of straw decomposition, microbial activities become active, and the increased microorganism and enzyme activities release a large amount of K that can be exchanged into the soil (T. Zhang *et al.* 2014). The straw application might release an alkaline substance that could increase soil pH and indicate a significant negative relationship between soil pH and K uptakes (X.-Z. Han *et al.* 2012). A positive interaction with soil pH might be in the slightly acidic (6.5) to slightly alkaline (7.5) range, where plant roots can easily uptake the nutrient from the soil (Hossain *et al.* 2014).

5. Conclusion

The present study shows incorporation of rice straw treatments was used to evaluate the accumulation of nutrients and soil availability of nutrients in a variety of green manure species. Among all species, shoot and root phosphorus use efficiency improved in peas on T3 treatments (particularly in the amount of 7500 kg ha^{-1}). The addition of rice straw incorporation (T3) increased soil nitrogen and available potassium. Treatments involving straw incorporation decreased the readily available P content in the soil. However, it did not change the pattern of available phosphorus content in the soil solution during crop growth. The practice of incorporating straw into the soil can prevent environmental pollution, is an effective method to improve the quality of soil nutrients in Pakistan and can also reduce the high fertilizer consumption in crop production. In this regard, more studies are needed to clarify long-term experiments on legume and non-legumes (green manure) crops under rice straw treatments combined with fertilizer application.

Author Contributions

Conceptualization, F.S., and X.Z.; Methodology, F.S.; Validation, X.Z. Formal Analysis, F.S.; and K.A.S.; Investigation., F.S.; Data Collection, K.A.S.; Writing—Original Draft Preparation, F.S.; Writing—Review and Editing, X.Z. H.Y, and K.A.S.; Funding Acquisition, X.Z. All of the authors contributed significantly to the completion of this review, conceiving and designing the review, and writing and improving the paper.

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Data availability

The datasets analyzed during this study are included in this manuscript.

Ethics approval and consent to participate

This study does not include human or animal subjects.

Consent for publication

Not applicable.

Competing interests

The authors stated that they had no interest which might be perceived as posing a conflict or bias.

References

Abd–Elrahman, S. H., Saudy, H. S., El–Fattah, D. A. A., & Hashem, F. A. (2022). Effect of Irrigation Water and Organic Fertilizer on Reducing Nitrate Accumulation and Boosting Lettuce Productivity. *Journal of Soil Science and Plant Nutrition*, *22*(2), 2144–2155. https://doi.org/10.1007/s42729-022-00799-8

Aleixo, G. T., Afonso, C. R. M., Coelho, A. A., & Caram, R. (2008). Effects of omega phase on elastic modulus of Ti-Nb alloys as a function of composition and cooling rate. *Solid State Phenomena*, *138*, 393–398. https://doi.org/10.4028/www.scientific.net/SSP.138.393

Ali, M. Z., Alam, M. S., Rahman, G. K. M. M., Rahman, M. M., Islam, M. M., Kamal, M. Z., & Hossain, M. S. (2021). Short-term effect of rice straw application on soil fertility and rice yield. *Eurasian Journal of Soil Science*, *10*(1), 9–16. https://doi.org/10.18393/ejss.797847

Anwar, A., Ashfaq, M., Habib, S., Ahmad, M. S., Mazhar, H. S.-U.-D., Müller-Xing, R., & Javed, M. A. (2025). Improving the nutraceutical content of tomato (Lycopersicon esculentum) by advanced environmental conditions and agricultural practices. *Advancements in Life Sciences*, *12*(1), 13–22. https://submission.als-journal.com/index.php/ALS/article/view/1725

Ashraf, M. (2004). Some important physiological selection criteria for salt tolerance in plants. *Flora-Morphology, Distribution, Functional Ecology of Plants*, *199*(5), 361–376.

Chadwick, D., Wei, J., Yan, T., Guanghui, Y., Qirong, S., & Qing, C. (2015). Agriculture , Ecosystems and Environment Improving manure nutrient management towards sustainable agricultural intensi fi cation in China. *"Agriculture, Ecosystems and Environment."* https://doi.org/10.1016/j.agee.2015.03.025

Chivenge, P., Rubianes, F., Van Chin, D., Van Thach, T., Khang, V. T., Romasanta, R. R., Van Hung, N., & Van Trinh, M. (2020).

Rice Straw Incorporation Influences Nutrient Cycling and Soil Organic Matter. In *Sustainable Rice Straw Management*. https://doi.org/10.1007/978-3-030-32373-8_8

Du, K., Huang, J., Wang, W., Zeng, Y., Li, X., & Zhao, F. (2024). Monitoring Low-Temperature Stress in Winter Wheat Using TROPOMI Solar-Induced Chlorophyll Fluorescence. *IEEE Transactions on Geoscience and Remote Sensing*, *62*, 1–11. https://doi.org/10.1109/TGRS.2024.3351141

Eagle, A. J., Bird, J. A., Horwath, W. R., Linquist, B. A., Brouder, S. M., Hill, J. E., & van Kessel, C. (2000). Rice yield and nitrogen utilization efficiency under alternative straw management practices. *Agronomy Journal*, *92*(6), 1096–1103.

El-Mageed, T. A. A., Mekdad, A. A. A., Rady, M. O. A., Abdelbaky, A. S., Saudy, H. S., & Shaaban, A. (2022). Physio-biochemical and Agronomic Changes of Two Sugar Beet Cultivars Grown in Saline Soil as Influenced by Potassium Fertilizer. *Journal of Soil Science and Plant Nutrition*, *22*(3), 3636–3654. https://doi.org/10.1007/s42729-022-00916-7

Gaind, S., & Nain, L. (2007). Chemical and biological properties of wheat soil in response to paddy straw incorporation and its biodegradation by fungal inoculants. *Biodegradation*, *18*(4), 495–503.

Gupta, R. K., Yadvinder-Singh, Ladha, J. K., Bijay-Singh, Singh, J., Singh, G., & Pathak, H. (2007). Yield and Phosphorus Transformations in a Rice-Wheat System with Crop Residue and Phosphorus Management. *Soil Science Society of America Journal*, *71*(5), 1500–1507. https://doi.org/10.2136/sssaj2006.0325

Hammond, J. P., Broadley, M. R., White, P. J., King, G. J., Bowen, H. C., Hayden, R., Meacham, M. C., Mead, A., Overs, T., Spracklen, W. P., & Greenwood, D. J. (2009). Shoot yield drives phosphorus use efficiency in Brassica oleracea and correlates with root architecture traits. *Journal of Experimental Botany*, *60*(7), 1953–1968. https://doi.org/10.1093/jxb/erp083

Han, X., Xu, C., Dungait, J. A. J., Bol, R., Wang, X., Wu, W., & Meng, F. (2018). Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: A system analysis. *Biogeosciences*, *15*(7), 1933–1946. https://doi.org/10.5194/bg-15-1933-2018

Han, X.-Z., Zhu, L.-Q., Yang, M.-F., Yu, Q., & Bian, X.-M. (2012). Effects of different amount of wheat straw returning on rice growth, soil microbial biomass and enzyme activity. *Journal of Agro-Environment Science*, *31*(11), 2192–2199.

Hossain, I., Osman, K., ul Kashem, A., Sarker Imam Hossain, A., Kashem, A., & Sarker, A. (2014). Correlations of available phosphorus and potassium with pH and organic matter content in the different forested soils of Chittagong Hill Tracts, Bangladesh. *International Journal of Forest, Soil and Erosion (IJFSE) Int. J. Forest, Soil and Erosion*, *4*(41), 7–10.

Jin, Z., Shah, T., Zhang, L., Liu, H., Peng, S., & Nie, L. (2020). Effect of straw returning on soil organic carbon in rice–wheat rotation system: A review. In *Food and Energy Security* (Vol. 9, Issue 2). https://doi.org/10.1002/fes3.200

Jukanti, A. K., Gaur, P. M., Gowda, C. L. L., & Chibbar, R. N. (2012). Nutritional quality and health benefits of chickpea (Cicer arietinum L.): A review. *British Journal of Nutrition*, *108*(SUPPL. 1). https://doi.org/10.1017/S0007114512000797

Karami, A., Homaee, M., Afzalinia, S., Ruhipour, H., & Basirat, S. (2012). Organic resource management: Impacts on soil aggregate stability and other soil physico-chemical properties. *Agriculture, Ecosystems & Environment*, *148*, 22–28.

Lan, Z. M., Lin, X. J., Wang, F., Zhang, H., & Chen, C. R. (2012). Phosphorus availability and rice grain yield in a paddy soil in response to long-term fertilization. *Biology and Fertility of Soils*, *48*(5), 579–588. https://doi.org/10.1007/s00374-011-0650-5

Li, H., Zhang, T., Shaheen, S. M., Abdelrahman, H., Ali, E. F., Bolan, N. S., Li, G., & Rinklebe, J. (2022). Microbial inoculants and struvite improved organic matter humification and stabilized phosphorus during swine manure composting: Multivariate and multiscale investigations. *Bioresource Technology*, *351*. https://doi.org/10.1016/j.biortech.2022.126976

Liu, J., Wang, Y., Li, Y., Peñuelas, J., Zhao, Y., Sardans, J., Tetzlaff, D., Liu, J., Liu, X., Yuan, H., Li, Y., Chen, J., & Wu, J. (2023). Soil ecological stoichiometry synchronously regulates stream nitrogen and phosphorus concentrations and ratios. *Catena*, *231*. https://doi.org/10.1016/j.catena.2023.107357

Lou, Y., Xu, M., Wang, W., Sun, X., & Zhao, K. (2011). Return rate of straw residue affects soil organic C sequestration by chemical fertilization. *Soil and Tillage Research*, *113*(1), 70–73. https://doi.org/10.1016/j.still.2011.01.007

Mao, H., Liu, Y., Wang, Y., Ma, G., Wang, B., Du, X., Shi, Q., & Ni, J. (2022). Response of growth, photosynthesis, dry matter partition and roots to combined nitrogen–potassium stress in cucumber. *Quality Assurance and Safety of Crops & Foods*, *14*(4), 45–53. https://www.qascf.com/index.php/qas/article/view/1065

Martinez-Feria, R. A., Castellano, M. J., Dietzel, R. N., Helmers, M. J., Liebman, M., Huber, I., & Archontoulis, S. V. (2018). Linking crop- and soil-based approaches to evaluate system nitrogen-use efficiency and tradeoffs. *Agriculture, Ecosystems and Environment*, *256*, 131–143. https://doi.org/10.1016/j.agee.2018.01.002

Moe, K., Mg, K. W., Win, K. K., & Yamakawa, T. (2017). Effects of combined application of inorganic fertilizer and organic manures on nitrogen use and recovery efficiencies of hybrid rice (Palethwe-1). *American Journal of Plant Sciences*, *8*(05), 1043.

Moll, R. H., Kamprath, E. J., & Jackson, W. A. (1982). Analysis and Interpretation of Factors Which Contribute to Efficiency of Nitrogen Utilization 1 . *Agronomy Journal*, *74*(3), 562–564. https://doi.org/10.2134/agronj1982.00021962007400030037x

Mubarak, M., Salem, E. M. M., Kenawey, M. K. M., & Saudy, H. S. (2021). Changes in Calcareous Soil Activity, Nutrient Availability, and Corn Productivity Due to The Integrated Effect of Straw Mulch and Irrigation Regimes. *Journal of Soil Science and Plant Nutrition*, *21*(3), 2020–2031. https://doi.org/10.1007/s42729-021-00498-w

Murphy, J., & Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, *27*, 31–36.

Nelson, D. W., & Sommers, L. E. (2018). Total carbon, organic carbon, and organic matter. In *Methods of Soil Analysis, Part 3: Chemical Methods* (pp. 961–1010). https://doi.org/10.2136/sssabookser5.3.c34

Noureldin, N. A., Saudy, H. S., Ashmawy, F., & Saed, H. M. (2013). Grain yield response index of bread wheat cultivars as influenced by nitrogen levels. *Annals of Agricultural Sciences*, *58*(2), 147–152. https://doi.org/10.1016/j.aoas.2013.07.012

Osman, K. T. (2013). Problem soils and their management. In *Soils* (pp. 161–174). Springer.

Ozturk, L., Eker, S., Torun, B., & Cakmak, I. (2005). Variation in phosphorus efficiency among 73 bread and durum wheat genotypes grown in a phosphorus-deficient calcareous soil. *Plant and Soil*, *269*(1–2), 69–80. https://doi.org/10.1007/s11104-004-0469-z

Qiu, S., Yang, H., Zhang, S., Huang, S., Zhao, S., Xu, X., He, P., Zhou, W., Zhao, Y., Yan, N., Nikolaidis, N., Christie, P., & Banwart, S. A. (2023). Carbon storage in an arable soil combining field measurements, aggregate turnover modeling and climate scenarios. *Catena*, *220*. https://doi.org/10.1016/j.catena.2022.106708

Qiu, S.-J., Peng, P.-Q., Li, L., He, P., Liu, Q., Wu, J.-S., Christie, P., & Ju, X.-T. (2012). Effects of applied urea and straw on various nitrogen fractions in two Chinese paddy soils with differing clay mineralogy. *Biology and Fertility of Soils*, *48*(2), 161–172.

Rasool, G., Guo, X., Wang, Z., Ali, M. U., Chen, S., Zhang, S., Wu, Q., & Ullah, M. S. (2020). Coupling fertigation and buried straw layer improves fertilizer use efficiency, fruit yield, and quality of greenhouse tomato. *Agricultural Water Management*, *239*, 106239. https://www.sciencedirect.com/science/article/pii/S0378377420301335

Salem, E. M. M., Kenawey, M. K. M., Saudy, H. S., & Mubarak, M. (2022). Influence of Silicon Forms on Nutrients Accumulation and Grain Yield of Wheat Under Water Deficit Conditions. *Gesunde Pflanzen*, *74*(3), 539–548. https://doi.org/10.1007/s10343-022-00629-y

Saudy, H., Noureldin, N., Mubarak, M., Fares, W., & Elsayed, M. (2020). Cultivar selection as a tool for managing soil phosphorus and faba bean yield sustainability. *Archives of Agronomy and Soil Science*, *66*(3), 414–425. https://doi.org/10.1080/03650340.2019.1619078

Saudy, H. S., Abd El–Momen, W. R., & El–Khouly, N. S. (2018). Diversified nitrogen rates influence nitrogen agronomic efficiency and seed yield response index of sesame (Sesamum Indicum, L.) cultivars. *Communications in Soil Science and Plant Analysis*, *49*(19), 2387–2395. https://doi.org/10.1080/00103624.2018.1510949

Saudy, H. S., & El–Metwally, I. M. (2019). Nutrient Utilization Indices of NPK and Drought Management in Groundnut under Sandy Soil Conditions. *Communications in Soil Science and Plant Analysis*, *50*(15), 1821–1828. https://doi.org/10.1080/00103624.2019.1635147

Schönleber, M., & Ivers-Tiffée, E. (2015). Approximability of impedance spectra by RC elements and implications for impedance analysis. *Electrochemistry Communications*, *58*, 15–19. https://doi.org/10.1016/j.elecom.2015.05.018

Shaaban, A., El-Mageed, T. A. A., El-Momen, W. R. A., Saudy, H. S., & Al-Elwany, O. A. A. I. (2023). The Integrated Application of Phosphorous and Zinc Affects the Physiological Status, Yield and Quality of Canola Grown in Phosphorus-suffered Deficiency Saline Soil. *Gesunde Pflanzen*. https://doi.org/10.1007/s10343-023-00843-2

Sial, T. A., Liu, J., Zhao, Y., Khan, M. N., Lan, Z., Zhang, J., Kumbhar, F., Akhtar, K., & Rajpar, I. (2019). Co-application of milk tea waste and NPK fertilizers to improve sandy soil biochemical properties and wheat growth. *Molecules*, *24*(3), 1–17. https://doi.org/10.3390/molecules24030423

Singh, V. K., Dwivedi, B. S., Singh, S. K., Mishra, R. P., Shukla, A. K., Rathore, S. S., Shekhawat, K., Majumdar, K., & Jat, M. L. (2018). Effect of tillage and crop establishment, residue management and K fertilization on yield, K use efficiency and apparent K balance under rice-maize system in north-western India. *Field Crops Research*, *224*, 1–12.

Solangi, F., Bai, J., Gao, S., Yang, L., Zhou, G., & Cao, W. (2019). Improved accumulation capabilities of phosphorus and potassium in green manures and its relationship with soil properties and enzymatic activities. *Agronomy*, *9*(11). https://doi.org/10.3390/agronomy9110708

Solangi, F., Zhu, X., Cao, W., Dai, X., Solangi, K. A., Zhou, G., & Alwasel, Y. A. (2024). Nutrient Uptake Potential of Nonleguminous Species and Its Interaction with Soil Characteristics and Enzyme Activities in the Agro-ecosystem. *ACS Omega*, *9*(12), 13860–13871. https://doi.org/10.1021/acsomega.3c08794

Solangi, F., Zhu, X., Khan, S., Rais, N., Majeed, A., Sabir, M. A., Iqbal, R., Ali, S., Hafeez, A., Ali, B., Ercisli, S., & Kayabasi, E. T. (2023). The Global Dilemma of Soil Legacy Phosphorus and Its Improvement Strategies under Recent Changes in Agro-Ecosystem Sustainability. *ACS Omega*, *8*(26), 23271–23282. https://doi.org/10.1021/acsomega.3c00823

Solangi, K. A., Siyal, A. A., Wu, Y., Abbasi, B., Solangi, F., Lakhiar, I. A., & Zhou, G. (2019). An assessment of the spatial and temporal distribution of soil salinity in combination with field and satellite data: A case study in Sujawal district. *Agronomy*, *9*(12). https://doi.org/10.3390/agronomy9120869

Soon, Y. K., & Kalra, Y. P. (1995). Short communication: A comparison of plant tissue digestion methods for nitrogen and phosphorus analyses. *Canadian Journal of Soil Science*, *75*(2), 243–245. https://doi.org/10.4141/cjss95-034

Stagnari, F., Maggio, A., Galieni, A., & Pisante, M. (2017). Multiple benefits of legumes for agriculture sustainability: An overview. *Chemical and Biological Technologies in Agriculture*, *4*(1), 1–13. https://doi.org/10.1186/s40538-016-0085-1

Tan, D., Liu, Z., Jiang, L., Luo, J., & Li, J. (2017). Long-term potash application and wheat straw return reduced soil potassium fixation and affected crop yields in North China. *Nutrient Cycling in Agroecosystems*, *108*(2), 121–133.

Thomas, G. W. (1996). Methods of Soil Analysis. Part 3. Chemical Methods. In *Methods of Soil Analysis. Part 3. Chemical Methods, SSSA and ASA, Madison, WI* (pp. 475–490).

Tsialtas, I. T., Baxevanos, D., Vlachostergios, D. N., Dordas, C., & Lithourgidis, A. (2018). Cultivar complementarity for symbiotic nitrogen fixation and water use efficiency in pea-oat intercrops and its effect on forage yield and quality. *Field Crops Research*, *226*, 28–37.

Vose, P. B. (1987). Genetical aspects of mineral nutrition—Progress to date. In *Genetic Aspects of Plant Mineral Nutrition* (pp. 3–13). https://doi.org/10.1007/978-94-009-3581-5_1

Walker, J. M., & Barber, S. A. (1962). Absorption of potassium and rubidium from the soil by corn roots. *Plant and Soil*, *17*(2), 243–259. https://doi.org/10.1007/BF01376227

Wang, H. Y., Shen, Q. H., Zhou, J. M., Wang, J., Du, C. W., & Chen, X. Q. (2011). Plants use alternative strategies to utilize nonexchangeable potassium in minerals. *Plant and Soil*, *343*(1–2), 209–220. https://doi.org/10.1007/s11104-011-0726-x

Wang, X., Huang, J., Feng, Q., & Yin, D. (2020). Winter wheat yield prediction at county level and uncertainty analysis in main wheat-producing regions of China with deep learning approaches. *Remote Sensing*, *12*(11). https://doi.org/10.3390/rs12111744

Wang, X., Jia, Z., Liang, L., Zhao, Y., Yang, B., Ding, R., Wang, J., & Nie, J. (2018). Changes in soil characteristics and maize yield under straw returning system in dryland farming. *Field Crops Research*, *218*, 11–17.

Wang, X., Yang, H., Liu, J., Wu, J., Chen, W., Wu, J., Zhu, L., & Bian, X. (2015). Effects of ditch-buried straw return on soil organic carbon and rice yields in a rice–wheat rotation system. *Catena*, *127*, 56–63.

Yadvinder-Singh, Gupta, R. K., Jagmohan-Singh, Gurpreet-Singh, Gobinder-Singh, & Ladha, J. K. (2010). Placement effects on rice residue decomposition and nutrient dynamics on two soil types during wheat cropping in rice-wheat system in northwestern India. *Nutrient Cycling in Agroecosystems*, *88*(3), 471–480. https://doi.org/10.1007/s10705-010-9370-8

Yan, C., Zhan, H., Yan, S., Dong, S., Ma, C., Song, Q., Gong, Z., & Barbie, M. (2016). Effects of straw retention and phosphorous fertilizer application on available phosphorus content in the soil solution during rice growth. *Paddy and Water Environment*, *14*(1), 61–69. https://doi.org/10.1007/s10333-015-0478-y

Yang, M., Fu, M., & Zhang, Z. (2021). The adoption of digital technologies in supply chains: Drivers, process and impact. *Technological Forecasting and Social Change*, *169*. https://doi.org/10.1016/j.techfore.2021.120795

Yang, X., Zhang, K., Chang, T., Shaghaleh, H., Qi, Z., Zhang, J., Ye, H., & Hamoud, Y. A. (2024). Interactive Effects of Microbial Fertilizer and Soil Salinity on the Hydraulic Properties of Salt-Affected Soil. *Plants*, *13*(4). https://doi.org/10.3390/plants13040473

Yao, S., Teng, X., & Zhang, B. (2015). Effects of rice straw incorporation and tillage depth on soil puddlability and mechanical properties during rice growth period. *Soil and Tillage Research*, *146*, 125–132.

Zelazny, L. W., He, L., & Vanwormhoudt, A. M. (2018). Charge analysis of soils and anion exchange. In *Methods of Soil Analysis, Part 3: Chemical Methods* (pp. 1231–1253). https://doi.org/10.2136/sssabookser5.3.c41

Zhang, P., Chen, X., Wei, T., Yang, Z., Jia, Z., Yang, B., Han, Q., & Ren, X. (2016). Effects of straw incorporation on the soil nutrient contents, enzyme activities, and crop yield in a semiarid region of China. *Soil and Tillage Research*, *160*, 65–72.

Zhang, T., Li, H., Yan, T., Shaheen, S. M., Niu, Y., Xie, S., Zhang, Y., Abdelrahman, H., Ali, E. F., Bolan, N. S., & Rinklebe, J. (2023). Organic matter stabilization and phosphorus activation during vegetable waste composting: Multivariate and multiscale investigation. *Science of the Total Environment*, *891*. https://doi.org/10.1016/j.scitotenv.2023.164608

Zhang, T., Li, P., Fang, C., & Jiang, R. (2014). Phosphate recovery from animal manure wastewater by struvite crystallization and CO2 degasification reactor. *Ecological Chemistry and Engineering S*, *21*(1), 89–99. https://doi.org/10.2478/eces-2014-0008

Zhang, Y., Liu, Y., Zhang, G., Guo, X., Sun, Z., & Li, T. (2018). The effects of rice straw and biochar applications on the microbial community in a soil with a history of continuous tomato planting history. *Agronomy*, *8*(5). https://doi.org/10.3390/agronomy8050065

Zhang, Z., Liu, D., Wu, M., Xia, Y., Zhang, F., & Fan, X. (2021). Long-term straw returning improve soil K balance and potassium supplying ability under rice and wheat cultivation. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-01594-8

Zhao, X., Wang, J., Wang, S., & Xing, G. (2014). Successive straw biochar application as a strategy to sequester carbon and improve fertility: A pot experiment with two rice/wheat rotations in paddy soil. *Plant and Soil*, *378*(1), 279–294.

Zhao, X., Yuan, G., Wang, H., Lu, D., Chen, X., & Zhou, J. (2019). Effects of full straw incorporation on soil fertility and crop yield in rice-wheat rotation for silty clay loamy cropland. *Agronomy*, *9*(3). https://doi.org/10.3390/agronomy9030133