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ENHANCING CROP YIELD AND SOIL PROPERTIES THROUGH RESIDUE MANAGEMENT IN ERODED LANDS: PREDICTIVE INSIGHTS USING ANN AND MLR MODELS

NADIA AFSAR
Department of Soil and Environmental Sciences, University of Poonch, Rawalakot Azad Jammu and Kashmir-Pakistan.

AQILA SHAHEEN*
Department of Soil and Environmental Sciences, University of Poonch, Rawalakot Azad Jammu and Kashmir-Pakistan. *Corresponding Author Email: aqeela.shaheen@gmail.com

ABDUL KHALIQ
Department of Soil and Environmental Sciences, University of Poonch, Rawalakot Azad Jammu and Kashmir-Pakistan.

ARSHAD ASHRAF
Principle Scientific Officer, CEWRI, National Agriculture Research Center Islamabad-Pakistan.

ABDUL HAMID
Vice Chancellor, Women University of Bagh Azad Jammu & Kashmir.

Abstract
Crop residues improve soil fertility and health while lessening the soil's vulnerability to erosion in sub-mountainous regions. From 2016 to 2018, a randomized complete block design (RCBD) experiment was carried out. There were 18 treatments made from the residue types of wheat straw (WR) and maize stover (MR), applied at 0, 4, and 6 Mg ha^{-1}. Wheat and maize crops were planted alternately. The combined data from 2016–17 and 2017–18 demonstrated that crop residue increased wheat grain yield over control by 74% and 83%, respectively, at 4 and 6 Mg ha^{-1}. Similarly, at both 4 and 6 Mg ha^{-1} of crop residues, the grain yield of maize increased by 25% between 2016 and 2018. Residue types, MR yielded 12% higher maize grain than WR. The four seasons (2016, 2016–17, 2017 and 2017–18) revealed a higher bulk density (BD), lower total nitrogen (TN), and lower organic matter (OM) without residue incorporation. Higher soil water (SW) contents, higher soil OM, and lower soil bulk density (BD) were observed in the fourth season following the harvest of two wheat and two maize crops. The percent increase in OM was 16, TN 50 and a decrease in BD 4.5 in the fourth season postharvest compared to presowing soil properties. A linear model using multiple linear regression (MLR) and a non-linear model artificial neural networks (ANN) were applied using actual crop yield data, soil properties, and meteorological information. The ANN model slightly outperforms the MLR model in accuracy and explaining yield variation. Thus, the ANN model is more reliable for predicting crop yields based on the data provided. Adding crop residues increases crop yield by improving soil properties.

Keywords: Wheat and Maize Residues; Yield; Soil Erosion; Soil Conservation, MLR Model, ANN Model.

INTRODUCTION
Crop residues are materials high in carbon that are also rich in both micronutrients and macronutrients including phosphorus (P), potassium (K), and nitrogen (N).

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A sustainable method of enhancing soil quality is through the application of crop residue as organic input (Fu et al., 2021). Every year, the amount of crop residues rises in tandem with population growth. There is 2445.2 MT of crop residues produced worldwide (Jin et al., 2020). However, Shinde et al. (2022) estimated that the global production of crop residues was five billion metric tons in 2020–2021. Reintroducing crop residues into the soil is a current strategy to maintain soil OM, enhance physical attributes, ecological activity, and recycle nutrients, particularly N (Smitha et al., 2019). The agriculture sector is under immense pressure to fulfill the increasing industrial and food demands because of economic development and rapid population growth (Taheri, 2017). As a result, farmers frequently use unsustainable techniques, like burning crop residues to make way for new crop plantings (Khokhar et al., 2015). Massive burning of crop residue has led to various health problems, smog, haze, heat waves, and a decline in air quality, soil degradation, increased soil erosion risk, negatively affects soil microorganisms, and ultimately reduces crop productivity (Bakhsh et al., 2018; Raza et al., 2019; Shinde et al., 2022; Lin and Begho 2022) in addition to large financial losses (Zhao et al., 2017). The burning of crop residues can be stopped by adopting sustainable crop residue management practices (SCRMPs) and empowering farmers to implement these (Raza et al., 2022).

Moreover, in many developing countries the harvested crop residues are utilized for food and fiber (household fuel, building materials, animal bedding and feed, paper manufacturing and mushroom cultivation) which has a detrimental impact on soil nutrient status, agronomic productivity and environmental quality (Maw et al, 2019).

Crop residue management is crucial for optimizing soil quality and sustainable farming practices. Crop residue management of 6 mg ha^{-1} is considered suitable for the right amount of soil cover and to stop soil carbon loss (Vasconcelos et al. 2018).

In cereal-cereal cropping systems crop residue application can increase soil quality and yield (Mirzaei et al., 2021). Various studies showed that the application of plant residues as a soil amendment can improve its properties (Li et al., 2021), which will provide a favorable environment for plant root development and give sustainable crop yield (Blanco-Canqui and Lal, 2009; Dhaliwal et al., 2019). Crop residue incorporation may also check soil erosion processes (Cerdà et al., 2018). Applying organic residues to the soil enhances its health, which increases crop productivity of crops like rice, wheat, and maize (Brichi et al., 2023). Organic residues are increasing in agriculture specifically for sustainability purposes (Dubey et al., 2020; Meena, Kumar, et al., 2019). Gupta et al., 2024 reported that crop residue retention in soil increased the yield of wheat.

In the mountainous topography, frequent heavy rainfall, particularly during the monsoon season, imbalance fertilizer application, less addition of OM and overall conventional farming practices collectively exacerbate soil erosion rates and lower yields. The abundance of crop residues, such as wheat and maize, can serve as valuable organic amendments for enhancing soil quality and boosting crop yields on eroded lands. The main objective of this study was to evaluate the impact of crop residues on both crop yields and soil characteristics.

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METHODOLOGY

Treatments and Experimental Design

The field experiments were performed at the Chotagala site from May 2016 to June 2018 at the experimental farm of the University of Poonch in Rawalakot. This location is positioned at a latitude of 33°51'32.18"N, a longitude of 73°45'34.93"E, and an elevation of 5374 feet (Figure 1). The site is prone to erosion due to high-intensity rainfall (Figure 2). The experimental sites have textural class silt loam, bulk density of 1.26 g cm^{-3}, and soil pH of 6.4. The percent organic matter was 2.2. Total nitrogen was 0.1% and available P and extractable K were 7.39 mg Kg^{-1} and 95.2 mg Kg^{-1}, respectively. Maize and wheat crops were selected based on the local farmers' priorities during the respective seasons. The two-year field experiment involved four crops, maize (June-October) and wheat (November-May) being sown in rotation over two years. The experiment followed a completely randomized design (RCBD) with three replications. Two crop residues i.e., wheat straw and maize stalk were used at different rates of 0, 4 and 6 $Mgha^{-1}$ making a total of 18 treatments. Before sowing of crops recommended rates of fertilizer nutrients N, P and K (Wheat NPK @ 120, 90, 60 kg ha^{-1}; maize NPK @ 120, 90, 60 kg ha^{-1}) was added into the soil in the form of Urea, diammonium phosphate (DAP) and sulphate of potash (SOP), respectively. Maize residues and wheat straw used in this investigation were collected in October 2015 from a local farmer's field. The composition of maize and wheat residues utilized for the experiment is given in Table 1.

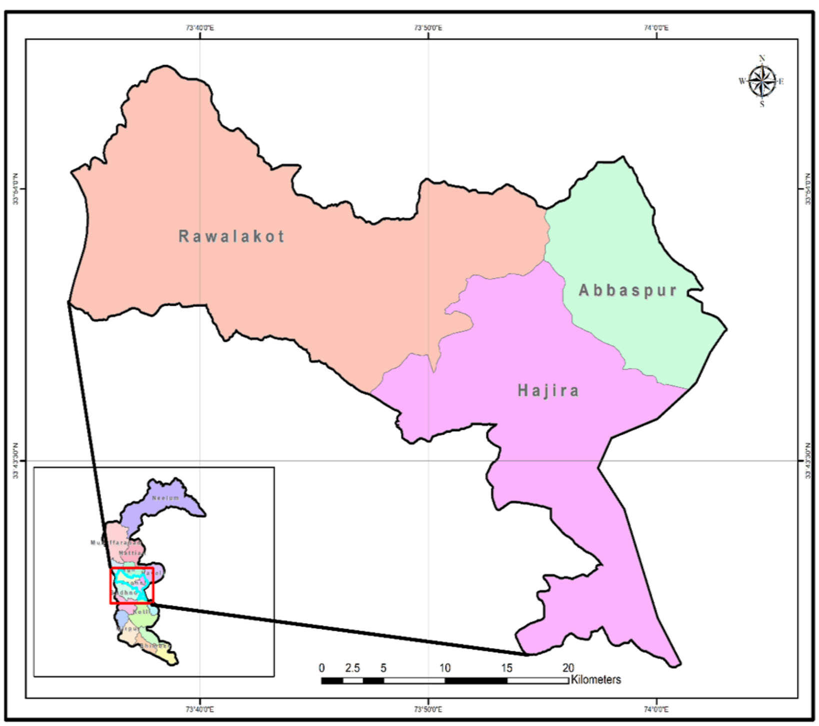

Figure 1: Geographical map of study area Rawalakot District Poonch Azad Jammu and Kashmir-Pakistan

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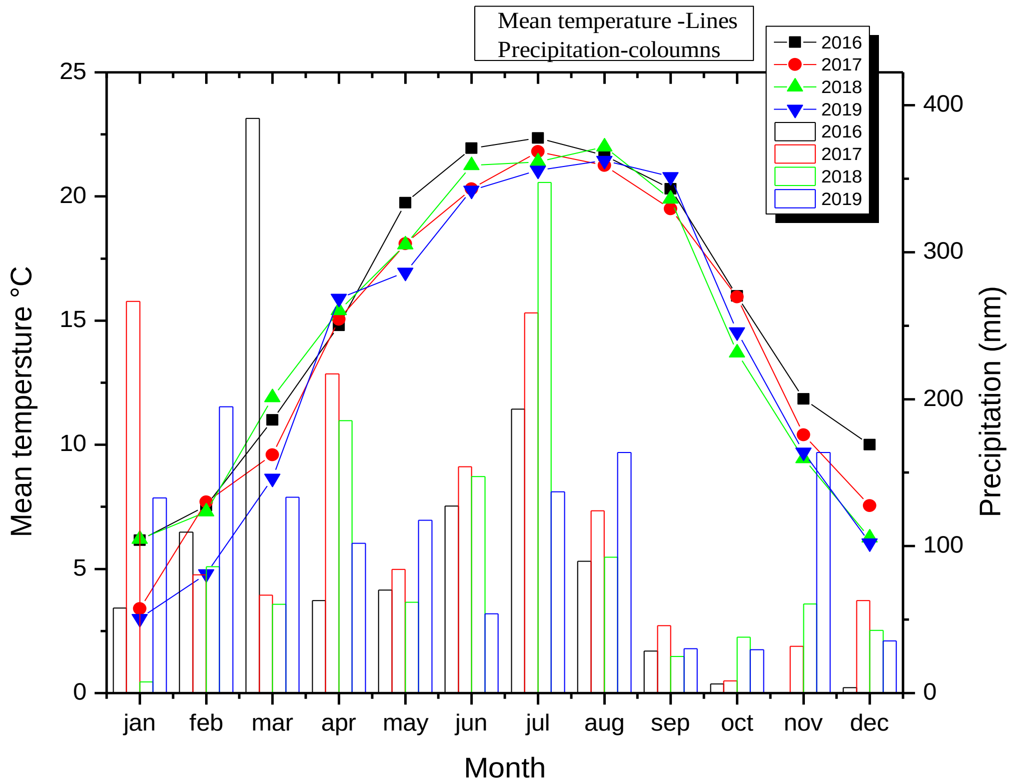

Figure 1: Meteorological data i.e., mean temperature (0C) and total rainfall (mm) of the experimental site of Chottagala Rawalakot for the year 2016-2019.

Table 1: The composition of maize and wheat residues utilized for the experiment

Chemical properties	Maize residues	Wheat straw residues
Total nitrogen (TN) g kg^{-1}	9.2	8.7
Available phosphorus (AP) g kg^{-1}	0.84	0.63
Extractable potassium (EK) g kg^{-1}	10.9	10.7
Total carbon (TC) g kg^{-1}	508	403
Organic matter (OM) g kg^{-1}	873.99	694.172
Moisture contents g kg^{-1}	689	739

Field Experiment

Experimental Procedure and Details

Before commencing the experiment and to ensure proper field bed preparation, the site was thoroughly ploughed and left for one week. The time of sowing was determined based on the sowing period of the specific crop and the availability of sufficient moisture in the field. Maize variety Kashmir gold was sown in the end of May and harvested in mid-October.

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For maize a row-to-row distance maintained at 55 cm and a plant-to-plant distance of 20-25 cm. After harvesting maize, the plots were manually ploughed and prepared for the next crop. Wheat variety inqlab 91 was sown in November and harvested in July. Wheat was sown at the end of October in rows spaced at 45 cm. After germination, the plant-to-plant distance was thinned to 6 cm. Throughout the cropping season, all plots were kept weed-free through manual hoeing. It’s a rainfed area so no irrigation was applied and all cultural practices throughout the season of both crops were followed.

The biological yield was calculated by harvesting each treatment entire plot. A sample of 200 grains was chosen at random of each treatment to determine the thousand-grain weight. The plant material was dispersed among the corresponding plots to dry in the sun. The bundles were manually threshed after drying, and the weight of the grain and stalk was noted.

The harvest index (HI) was calculated by using the following formula.

$$\text{“HI (\%)} = \frac{\text{Grain Yield}}{\text{Biological yield}} \times 100\text{”}$$

SOIL ANALYSES

Soil samples were collected at a depth of 0-15 cm from each treatment randomly, air dried, grounded, sieved and placed in jars to analyze for various physico-chemical characteristics after each crop harvest.

The analysis included measurements of pH, electrical conductivity (EC), water content, BD, TN, and OM. To determine the pH, a soil suspension of 1:2.5 (soil and water) was prepared and the electrode of the pH meter was inserted into the suspension to record the reading (McLean, 1982).

The electrical conductivity of the soil was measured using a soil suspension of 1:10 (soil and water) ratio and the reading was recorded with an EC meter after inserting its electrode in the suspension (Rhoades, 1982).

Following Page et al. (1982), the gravimetric method was used to determine the soil moisture content during the sowing and harvesting periods. Blake and Hartage (1986) core method were employed for assessing the bulk density of soil.

Using Bremner and Mulvaney's Kjeldahl method, the total nitrogen content of the soil was ascertained (1982). The Nelson and Sommers (1982) method was used to determine organic matter in the soil.

Statistical Analyses

The statistical method used by Steel et al. (1997) was applied to the data collected for different characteristics. The Statix 8 software was used for this purpose. The heat map, MLR and ANN models were created in Python. PCA was conducted using XLSTAT.

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RESULTS

Wheat

The combined data for years 2016-17 and 2017-18 (Table 2) indicated a statistically significant increase in grain yield with both 4 and 6 Mgha^{-1} rates of residue application, resulting in a percent increase of 74 and 83, respectively, compared to zero residue application. No statistical differences were observed between residue types and years. The straw yield was higher at the 6 Mg ha^{-1} rate followed by the 4 Mg ha^{-1} rate, with no differences observed between residue types. However, the yield was higher in 2017-18 compared to 2016-17.

The combined data from 2016-17 and 2017-18 revealed a higher 1000-grain weight with both rates of residue application, and the residue type WR had a higher grain weight than MR. The 1000-grain weight was similar in both years. In 2016-17, a higher harvest index was observed at 4 Mg ha^{-1} with residue type MR, however, the means showed a 63% and 53% increase in harvest index at 4 and 6 Mgha^{-1}, respectively. The residue types showed similar harvest indexes.

When data from both years were combined (Table 2), there was a 45% and 34% increase in harvest index with 4 and 6 Mgha^{-1} rates of application, respectively, compared to the 0 rate. There was no statistical difference in harvest index between the two residue types or between the two years.

Table 2: Influence of crop residue management on the grain yield, straw yield, 1000-grain weight and harvest index of wheat (Data is combined over years)

	Wheat grain yield (Mg ha^{-1})	**Straw yield (Mg ha^{-1})**	**1000-grain weight (g)**	**Harvest Index (%)**
Residue's rate (Mg ha^{-1})				
0	1.20 B	10.58 C	35.54 B	10.19 B
4	2.09 A	12.00 B	37.83 A	14.78 A
6	2.19 A	13.91 A	37.59 A	13. 68 A
Residue's type				
Maize residue	1.88 A	12.27 A	36.42 B	13.05 A
Wheat residue	1.77 A	12.06 A	37.56 A	12.72 A
Year				
2016-17	1.82 A	11.89 B	36.91 A	13.06 A
2017-18	1.83 A	12.44 A	37.06 A	12.70 A

Means sharing the same letters are statistically non-significant according to the LSD test ($P \leq 0.05$)

Maize

The combined data over 2016 and 2017 (Table 3) showed a statistically significant increase in maize grain yield with both rates of residue application (4 and 6 Mgha^{-1}), and the percent increase over zero application was 25% for both rates. The MR residue type had a higher grain yield than WR. The year 2017 had a higher yield than 2016.

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When combining the data from both years (Table 3), it was found that there was a 15% and 16% increase in stover yield with 4 and 6 $Mgha^{-1}$ rates of residue application, respectively, compared to no residue application. It was also observed that WR had a higher grain weight than MR, and the year 2017 had a higher weight than 2016. During 2016, MR at 4 $Mgha^{-1}$ had a higher harvest index, with means showing a 15% and 6% increase over no residue application. MR had a higher HI than WR. In contrast, the year 2017 had a lower HI with MR at 4 $Mgha^{-1}$ but means showed a 1.7% increase at 6 $Mgha^{-1}$ compared to no residue application. MR had a higher HI than WR. When combining the data over both years, there was a 7% and 4% increase in HI with 4 and 6 $Mgha^{-1}$, respectively, compared to no residue application. MR had a higher HI than WR, but both years showed statistically similar HI.

Table 3: Influence of crop residue management on the grain yield, stover yield, 1000-grain weight and harvest index of maize (Data is combined over year)

	Maize grain yield ($Mg\ ha^{-1}$)	Stover yield ($Mg\ ha^{-1}$)	1000-grain weight (g)	Harvest Index (%)
Residue's rate ($Mg\ ha^{-1}$)				
0	3.54 B	8.09 B	304.57 A	30.27 B
4	4.42 A	9.34 A	318.29 B	32.28 A
6	4.42 A	9.30 A	355.03 A	31.49 AB
Residue's type				
Maize residue	4.36 A	9.32 A	323.58 B	32.022 A
Wheat residue	3.89 B	8.73 B	328.34 A	30.67 B
Year				
2016	3.80 B	8.18 B	315.23 B	31.57 A
2017	4.45 A	9.87 A	336.69 A	31.16 A

Means sharing same letters are statistically non-significant according to the LSD test ($P \leq 0.05$)

Variations of Selected Soil Quality Indicators to Crop Residue Incorporation

The study investigated the effect of different rates of residue application on soil properties after a two-year crop rotation of maize and wheat (maize seasons= 2016 and 2017; wheat season= 2016-17 and 2017-18). The results, as shown in Figure 3a, indicate that a pH of 6.94 was observed with an application rate of 6 $Mgha^{-1}$, while 4 $Mgha^{-1}$ and 0 application rate had statistically similar pH values. No significant differences were observed in the electrical conductivity among the three rates of residue application. However, soil water content was 7% and 24% higher with 4 and 6 $Mg\ ha^{-1}$, respectively, compared to no residue application (R0). The bulk density was statistically higher in R0, and compared to R0, a 7% and 8% lower bulk density was observed in 4 $Mgha^{-1}$ and 6 $Mgha^{-1}$, respectively. The total nitrogen was statistically similar in all three rates of application, but the percent increase with 4 and 6 $Mgha^{-1}$ was 3% and 36%, respectively.

The organic matter content was higher in the 6 $Mgha^{-1}$ application rates, followed by 4 $Mgha^{-1}$. The percent increase in organic matter was 107% in 4 $Mgha^{-1}$ and 117% in 6

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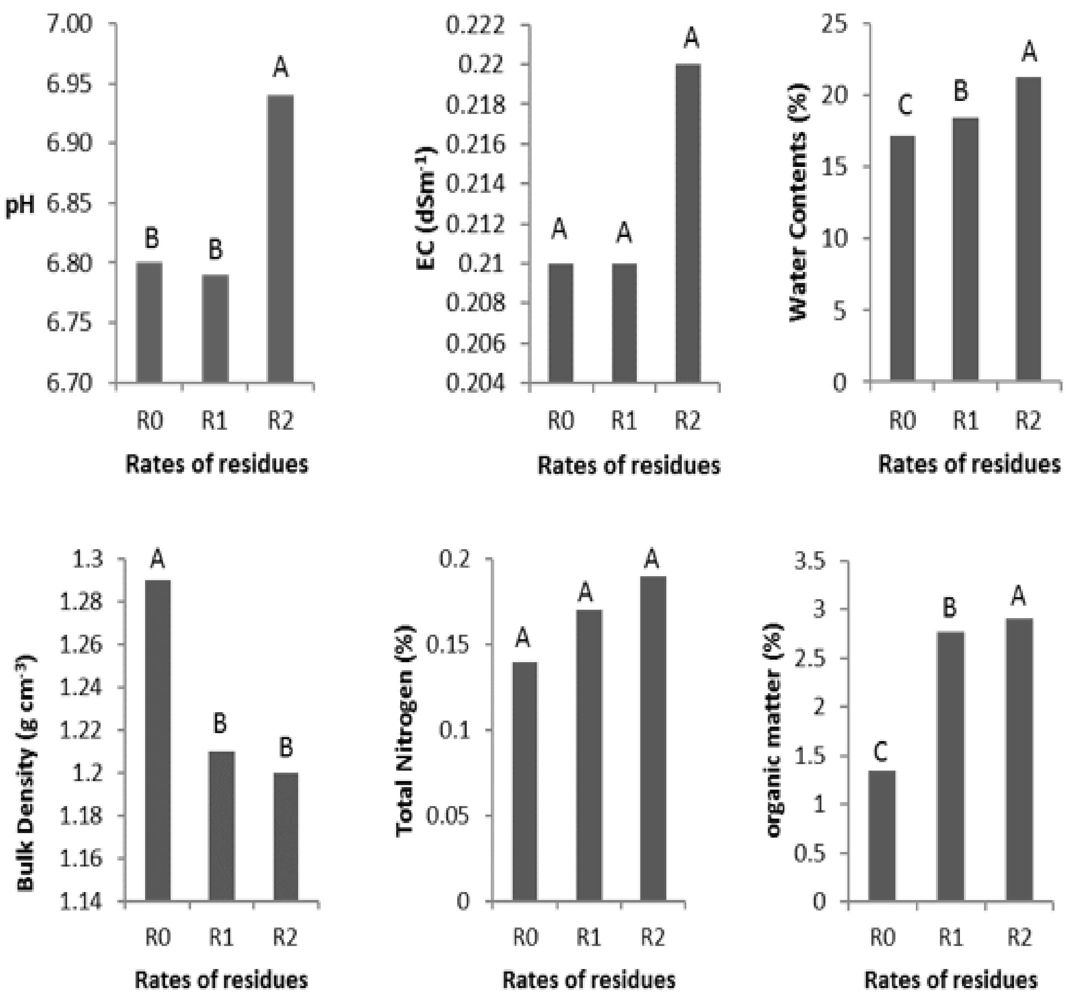
$Mgha^{-1}$ rate of application. The effect of residue type and season on soil properties was also investigated (Figure 3b and 3c). The results showed that pH, EC, WC, BD, TN, and OM were statistically similar between MR and WR types of residues (Figure 3b). However, there were slight differences in pH, organic matter, and total nitrogen, with slightly higher values observed in WR. Regarding the effect of season (Figure 3c), the pH decreased after season 1 but gradually increased to 6.95 after season 4. The EC slightly decreased after season 1, with a value of 0.27, and further reduced to 0.19 after season 4. The water content fluctuated after each season, with the lowest value of 13.03% observed in season 3, and the highest value of 25.54% after season 4. The bulk density was statistically higher after season 1 but gradually decreased to a lower value after season 4. The total nitrogen was higher after season 2, while seasons 1, 3, and 4 had statistically similar total nitrogen values. The organic matter content gradually increased after each season, with the highest value of 2.55% observed after season 4. The increase in organic matter content after 4 seasons was 21% compared to season 1.

a.



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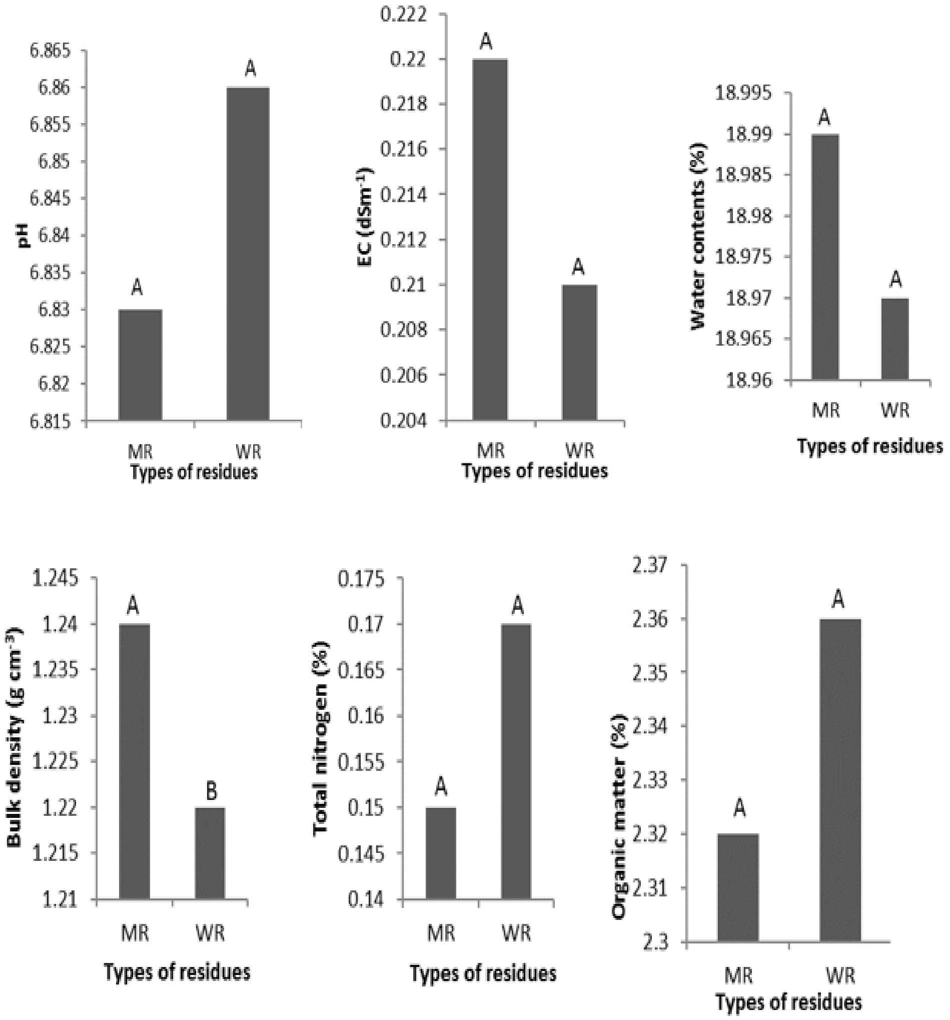
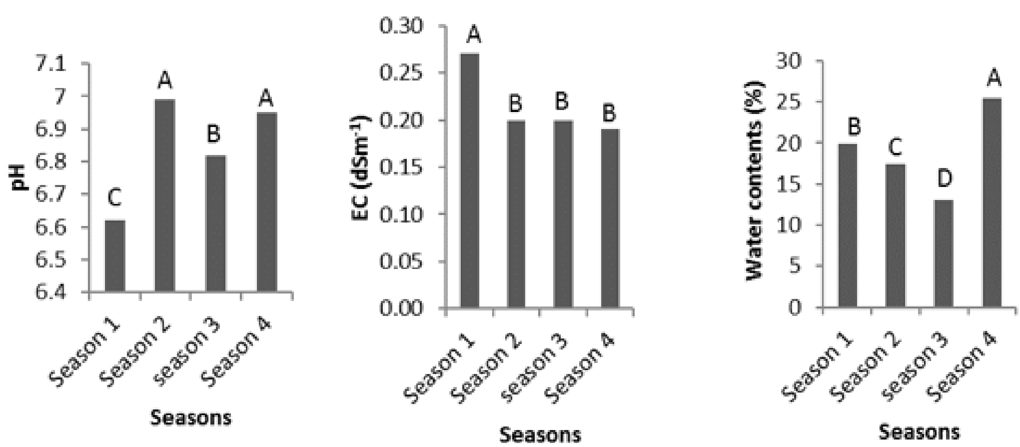
b.



c.



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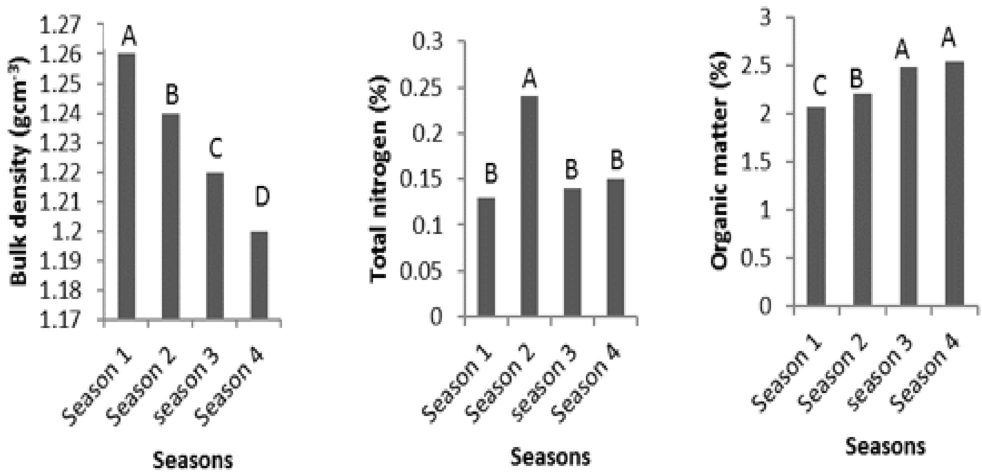

Figure 3: Variations of selected soil quality indicator measurements over four seasons. a. effect of rates of residues; b. effect of types of residues; c. effect of season. R0 no application of crop residues; R1 Residues application @ 4 Mg ha^{-1}; R2= Residues application @ 6 Mg ha^{-1}. MR= Maize residues; WR= Wheat residues. Season 1 is maize 2016; season 2 is wheat 2016-17; season 3 is maize 2017; season 4 is wheat 2017-18.

The means that share the same letters are not statistically significant at a p-value of ≤ 0.05.

Overall, the BD decreased in the last three seasons to the initial BD of 1.2 g cm^{-3}. The decrease of BD in the fourth season was 4.76 % as compared to the initial BD. The OM gradually increased after each season compared to presowing OM content of 2.2 %. The OM increased 16 % in fourth season compared to prosowing OM content. The TN compared to the initial status of 0.1% increased and in the fourth season, the increase was 50 %.

Principal Component Analysis

According to the Jolliffe cut-off value, the principal component analysis (PCA) allowed to isolate of five principal components. The observation point made by contact of PC1 and PC2 in PCA analysis (Figure 4) demonstrated the general difference distinct by the major five components. Component analysis of 12 variables (including, pH, EC, BD, AP, TN, AK, water contents, 1000 grain weight, Harvest index, stover yield, and grain yield) the eigenvalues >1 of PC1 and PC2 showed 59.45 % and 20.44 % of the total variance for Maize 2016. However, PC3, PC4, and PC5 were not plotted as these components did not give extra information. Similarly, for maize 2017 the PC1 and PC2 had 73.48 % and 14.14 % of variance, respectively. The component analysis of Wheat 2016-17 showed PC1 and PC2 70.82 % and 16.77 % of the total variance, respectively. The wheat season 2017-18 had PC1 66.53 % and PC2 16.9 % of total variance.

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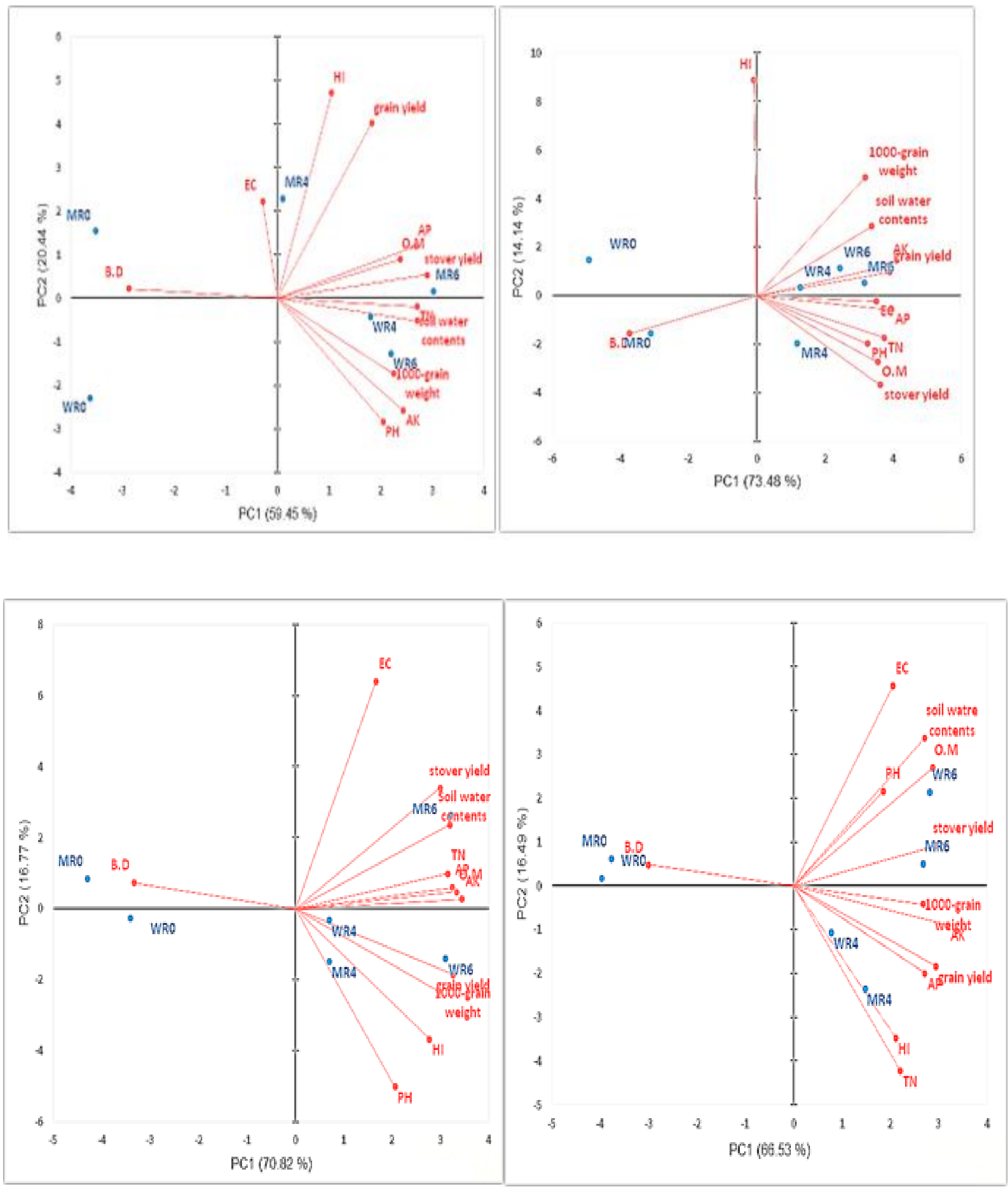
a. Maize 2016 b. Maize 2017



c. Wheat 2016-17 d. Wheat 2017-18

Figure 4: Principal component analysis of agronomic traits and soil with crop residue management. Note: (a) is the PCA analysis of maize 2016 crop; (b) is the PCA analysis of maize crop 2017 (c) is the PCA analysis of wheat crop 2016 - 2017; (d) is the PCA analysis of wheat crop 2017-2018

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Correlation of Agronomic Traits and Soil Properties

The correlation of agronomic characteristics and soil properties after four seasons. Following our hypothesis, the correlation between the agronomic characteristics of maize and wheat and soil total nitrogen contents and organic matter was significantly positive (Figure 5).

When crop residues are recycled in soil, the availability of N, P, K, and OM increases (Ali et al., 2020), reducing nutrient losses (Rasool et al., 2020), and enhancing crop yield.

a) Maize 2016

Variables	Grain yield	Stover yield	1000-grain weight	Harvest Index	Soil Water Contents	Bulk Density	pH	Electrical Conductivity	Organic matter	Total Nitrogen	Avail Phosphorus	Extractable Potassium
Grain yield	1	0.673	0.229	0.951	0.476	-0.541	-0.044	0.269	0.600	0.542	0.721	0.101
Stover yield	0.673	1	0.738	0.420	0.956	-0.887	0.652	0.136	0.684	0.930	0.811	0.700
1000-grain weight	0.229	0.738	1	-0.025	0.840	-0.599	0.535	-0.197	0.301	0.910	0.450	0.709
Harvest Index	0.951	0.420	-0.025	1	0.197	-0.301	-0.301	0.317	0.430	0.274	0.540	-0.151
Soil Water Contents	0.476	0.956	0.840	0.197	1	-0.783	0.723	0.175	0.492	0.953	0.629	0.708
Bulk Density	-0.541	-0.887	-0.599	-0.301	-0.783	1	-0.730	0.194	-0.881	-0.760	-0.936	-0.863
pH	-0.044	0.652	0.535	-0.301	0.723	-0.730	1	0.008	0.421	0.548	0.452	0.866
Electrical Conductivity	0.269	0.136	-0.197	0.317	0.175	0.194	0.008	1	-0.363	-0.015	-0.251	-0.363
Organic matter	0.600	0.684	0.301	0.430	0.492	-0.881	0.421	-0.363	1	0.541	0.964	0.611
Total Nitrogen	0.542	0.930	0.910	0.274	0.953	-0.760	0.548	-0.015	0.541	1	0.677	0.663
Available Phosphorus	0.721	0.811	0.450	0.540	0.629	-0.936	0.452	-0.251	0.964	0.677	1	0.669
Extractable Potassium	0.101	0.700	0.709	-0.151	0.708	-0.863	0.866	-0.363	0.611	0.663	0.669	1

a) Maize 2017

Variables	Grain yield	Stover yield	1000-grain weight	Harvest Index	Soil Water Contents	Bulk Density	pH	Electrical Conductivity	Organic matter	Total Nitrogen	Avail Phosphorus	Extractable Potassium
Grain yield	1	0.863	0.830	0.107	0.815	-0.899	0.726	0.747	0.827	0.941	0.948	0.906
Stover yield	0.863	1	0.536	-0.408	0.632	-0.718	0.754	0.753	0.920	0.935	0.892	0.775
1000-grain weight	0.830	0.536	1	0.429	0.898	-0.710	0.412	0.733	0.565	0.593	0.691	0.802
Harvest Index	0.107	-0.408	0.429	1	0.181	-0.213	-0.131	-0.160	-0.351	-0.132	-0.032	0.115
Soil Water Contents	0.815	0.632	0.898	0.181	1	-0.730	0.376	0.872	0.789	0.634	0.704	0.791
Bulk Density	-0.899	-0.718	-0.710	-0.213	-0.730	1	-0.836	-0.731	-0.716	-0.861	-0.946	-0.947
pH	0.726	0.754	0.412	-0.131	0.376	-0.836	1	0.615	0.576	0.806	0.899	0.851
Electrical Conductivity	0.747	0.753	0.733	-0.160	0.872	-0.731	0.615	1	0.822	0.650	0.779	0.866
Organic matter	0.827	0.920	0.565	-0.351	0.789	-0.716	0.576	0.822	1	0.859	0.816	0.734
Total Nitrogen	0.941	0.935	0.593	-0.132	0.634	-0.861	0.806	0.650	0.859	1	0.953	0.827
Available Phosphorus	0.948	0.892	0.691	-0.032	0.704	-0.946	0.899	0.779	0.816	0.953	1	0.954
Extractable Potassium	0.906	0.775	0.802	0.115	0.791	-0.947	0.851	0.866	0.734	0.827	0.954	1

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b) Wheat 2016-17

Variables	Grain yield	Stover yield	1000-grain weight	Harvest Index	Soil Water Contents	Bulk Density	pH	Electrical Conductivity	Organic matter	Total Nitrogen	Avail Phosphorus	Extractable Potassium
Grain yield	1	0.659	0.765	0.953	0.773	-0.863	0.611	0.179	0.764	0.877	0.706	0.889
Stover yield	0.659	1	0.539	0.403	0.900	-0.671	0.228	0.788	0.876	0.748	0.843	0.780
1000-grain weight	0.765	0.539	1	0.738	0.513	-0.914	0.678	0.172	0.787	0.692	0.746	0.725
Harvest Index	0.953	0.403	0.738	1	0.565	-0.789	0.655	-0.099	0.582	0.769	0.521	0.759
Soil Water Content	0.773	0.900	0.513	0.565	1	-0.752	0.322	0.664	0.848	0.827	0.847	0.936
Bulk Density	-0.863	-0.671	-0.914	-0.789	-0.752	1	-0.520	-0.385	-0.815	-0.894	-0.787	-0.912
pH	0.611	0.228	0.678	0.655	0.322	-0.520	1	-0.337	0.641	0.221	0.645	0.515
Electrical Conducti	0.179	0.788	0.172	-0.099	0.664	-0.385	-0.337	1	0.498	0.532	0.500	0.466
Organic matter	0.764	0.876	0.787	0.582	0.848	-0.815	0.641	0.498	1	0.689	0.990	0.867
Total Nitrogen	0.877	0.748	0.692	0.769	0.827	-0.894	0.221	0.532	0.689	1	0.634	0.885
Available Phosphoı	0.706	0.843	0.746	0.521	0.847	-0.787	0.645	0.500	0.990	0.634	1	0.863
Extractable Potassi	0.889	0.780	0.725	0.759	0.936	-0.912	0.515	0.466	0.867	0.885	0.863	1

c) Wheat 2017-18

Variables	Grain yield	Stover yield	1000-grain weight	Harvest Index	Soil Water Contents	Bulk Density	pH	Electrical Conductivity	Organic matter	Total Nitrogen	Avail Phosphorus	Extractable Potassium
Grain yield	1	0.788	0.675	0.884	0.638	-0.784	0.596	0.341	0.685	0.777	0.762	0.893
Stover yield	0.788	1	0.688	0.410	0.873	-0.833	0.562	0.559	0.820	0.473	0.845	0.859
1000-grain weight	0.675	0.688	1	0.501	0.674	-0.965	0.059	0.563	0.658	0.516	0.695	0.857
Harvest Index	0.884	0.410	0.501	1	0.283	-0.544	0.423	0.071	0.379	0.784	0.491	0.672
Soil Water Contents	0.638	0.873	0.674	0.283	1	-0.749	0.632	0.859	0.927	0.177	0.537	0.736
Bulk Density	-0.784	-0.833	-0.965	-0.544	-0.749	1	-0.238	-0.574	-0.761	-0.630	-0.842	-0.952
pH	0.596	0.562	0.059	0.423	0.632	-0.238	1	0.529	0.720	0.284	0.289	0.458
Electrical Conductivity	0.341	0.559	0.563	0.071	0.859	-0.574	0.529	1	0.890	0.021	0.252	0.552
Organic matter	0.685	0.820	0.658	0.379	0.927	-0.761	0.720	0.890	1	0.399	0.606	0.824
Total Nitrogen	0.777	0.473	0.516	0.784	0.177	-0.630	0.284	0.021	0.399	1	0.790	0.777
Available Phosphorus	0.762	0.845	0.695	0.491	0.537	-0.842	0.289	0.252	0.606	0.790	1	0.891
Extractable Potassium	0.893	0.859	0.857	0.672	0.736	-0.952	0.458	0.552	0.824	0.777	0.891	1

Figure 5: Heat map correlation of agronomic traits and soil properties after each growing season. Note: (a) is the heatmap correlation of agronomic traits and soil properties of maize crop 2016; (b) is the heatmap correlation of agronomic traits and soil properties of maize crop 2017; (c) is the heatmap correlation of agronomic traits and soil properties of wheat crop 2016-17 and (d) is the heatmap correlation of agronomic traits and soil properties of wheat crop 2017-18.

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Multiple Linear Regression Model

For the linear regression model (Figure 6), the training Mean Squared Error (MSE) was 0.0082, and the training R^2 was 0.9113. This indicates that during training, the model's predictions were very close to the actual results, with a low error and explaining about 91.13% of the variation in the actual results. When tested on new, unseen data, the model had a testing MSE of 0.0136 and a testing R^2 of 0.8487, showing slightly higher error but still explaining about 84.87% of the variation in the actual results.

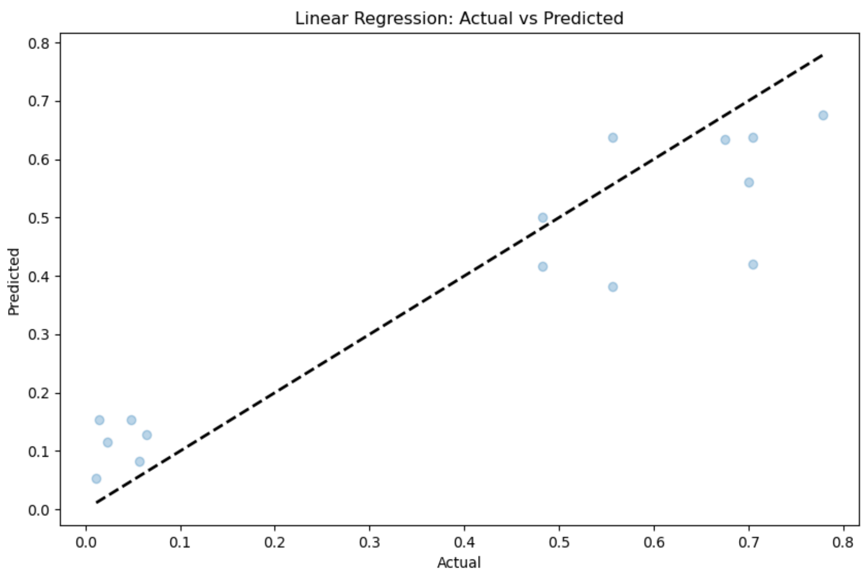

Figure 6: Linear Regression model comparing actual dataset values to the model's predicted values

Ann Model

The scatter plot titled "ANN: Actual vs Predicted" illustrates (Figure 7) the performance of an Artificial Neural Network (ANN) model by comparing actual dataset values to the model's predicted values. The overall trend indicates that the ANN model performs reasonably well, as data points generally align with the dashed line. Most points are close to the line, indicating accurate predictions, although there are some deviations, especially with lower actual values where over-prediction occurs. The spread of points around the line shows the variance in predictions, with a few outliers present.

For the ANN model during training, the Mean Squared Error (MSE) was 0.0077, and the R^2 was 0.9160, indicating that the model's predictions were very close to the actual results and explained about 91.60% of the variation in the actual results.

During testing, the MSE was 0.0066, and the R^2 was 0.9270, showing that the predictions were even closer to the actual results and explained about 92.70% of the variation in the actual results.

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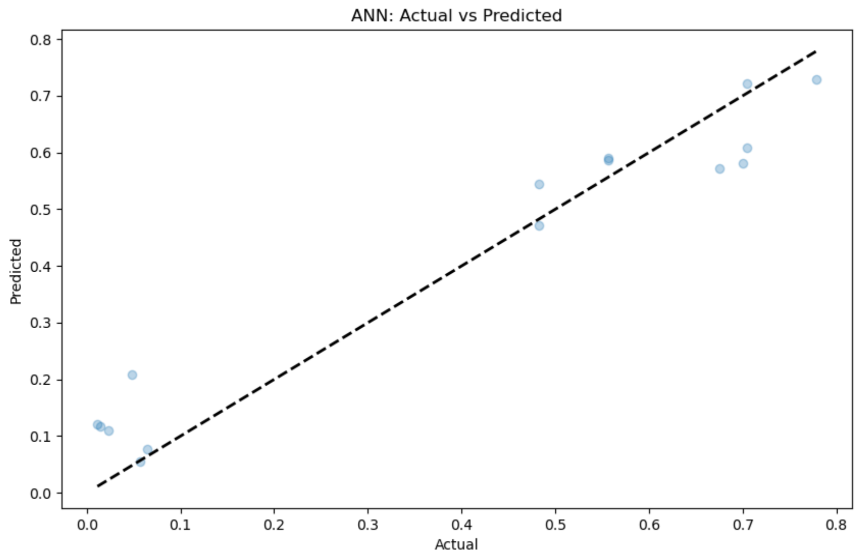

Figure 7: The scatter plot titled "ANN: Actual vs Predicted" illustrates the performance of an Artificial Neural Network (ANN) model by comparing actual dataset values to the model's predicted values. The x-axis displays actual dataset values, while the y-axis showcases predictions generated by the ANN model. Data points near the dashed line (y = x) signify precise predictions, with points precisely on the line indicating perfect alignment. This plot evaluates model performance: points close to the dashed line suggest good predictions, with points on the line being perfect. Points above the line indicate overestimation, while points below indicate underestimation

DISCUSSION

The findings of this study provide compelling evidence regarding the positive outcomes of incorporating crop residues in eroded lands. The substantial increase in wheat grain yield by 74% and 83% (Table 2) at residue rates of 4 Mg ha^{-1} and 6 Mg ha^{-1}, respectively, highlights the effectiveness of this residue management strategy in augmenting crop productivity. This aligns with previous research that underscores the role of crop residues in enhancing crop yields while also improving soil health.

The higher yield in amended plots is attributed to the improvement of soil conditions. The 25% enhancement in maize grain yield (Table 3) resulting from residue incorporation at both 4 Mg ha^{-1} and 6 Mg ha^{-1} further strengthens the argument for adopting residue management practices. The relatively higher yield increase observed with maize residues compared to wheat residues underscores the potential for residue type to influence specific crop responses. Many Studies showed that crop residue return has the potential to enhance both crop yield and quality (Cai *et al*., 2015; Xu et al., 2019a). Similarly, applying organic residues enhances soil health, leading to a positive impact on crop

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productivity in key crops like maize, wheat, and rice. (Brichi, *et al*..2023). Both types of residues increased wheat yield, however, in maize yield maize residue showed higher yield. This is attributed to higher macronutrients and organic matter content in maize residues compared to wheat residues. Crop residue return has an impact on a variety of factors, including soil properties, tillage intensity, fertilization rate, crop residue types, return ratios, and return methods (Su et al., 2020). Consistently plowing at a uniform depth while removing all crop residues significantly diminishes the yields of major cereals such as wheat and maize within the wheat-maize cropping system (Shaheen and Sabir, 2017). Studies showed that crop residue return elevates crop yields by a relative increase of 5.0% compared to crops grown without this practice (Lu, 2020). Crop residue incorporation improved maize yield by 12% (Piccoli *et al*., 2020). Both higher Harvest Index and higher 1000-grain weight, in conjunction with the application of crop residues, are attributed to higher grain yield and improved soil properties, which in turn enhance overall yield and eventually contribute to the improvement of both HI and 1000-grain weight. Kamkar et al. (2014) observed that the application of residue resulted in the highest grain yield and 1000-grain weight. Juan et al., 2024 reported a substantial enhancement in the grain yield of wheat and maize, as well as their yield components, including 100 or 1000-grain weight with the application of crop residues with fertilizers. The residue application in the soil increases root growth, water and nutrient uptake and ultimately it leads to a higher HI in maize crops (Saeed et al. 2001).

The soil properties investigation shows the effects of residues on soil health. The higher BD, reduced TN and lower OM in the control align with degradation associated with poor management practices and higher rate of removal of soil organic material. The contrasting effects observed after incorporating maize residues, including increased soil water content and bulk density, accentuate the capacity of residue incorporation to mitigate these negative trends. The higher rate of 6 Mg ha^{-1} of residue incorporation showed a positive effect on postharvest soil properties, and it is attributed to the higher addition of organic matter and consequently improvement of the soil's physical condition. Both types of residues were effective and improved the soil properties. Crop residue returning can increase the content of organic carbon, nitrogen, available phosphorus, and potassium in soils and soil water contents (Zhao et al., 2019; Fu et al., 2021).

Our results concur with earlier studies that demonstrated that adding organic residues to soil maintains its pH and provides the macronutrients, particularly N and P. In agricultural production systems, adding organic sources to preserve soil fertility also helps to improve the physical state of the soil over the long run (Brichi et al., 2023).

Following crop residue amendment, soil WC, OC content, and TN increased. Crop residue incorporation has been shown in numerous studies to improve soil quality (Lal, 2005; Li et al., 2021). According to earlier research, properly managed additions of organic residue to the soil can support the preservation of OM and nutrient availability (Manna et al., 2018; Meena, Biswas, et al., 2019). Soil OM, and WC increased over the season due to the build-up of soil OM, however, soil TN increased in the second season and then lowered in seasons three and four could be due to leaching of N and

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immobilization. The rate and content of nutrient release are influenced by several factors, including the characteristics of crop residues (such as C/N ratio and chemical composition), climatic conditions (like temperature and moisture), soil attributes (such as pH and water content), and the method of application (direct versus indirect) (Grzyb et al., 2020). Crop residues can be added to the soil to raise moisture content (Zhao et al., 2019). Our findings align with earlier research (Tan et al., 2015; Ali et al., 2020), indicating that returning crop residue can elevate the soil levels of organic carbon, N, and other essential macronutrients. Applying crop residue to the soil can increase the availability of vital nutrients and stop nutrient loss (Zhang et al., 2021; Rasool et al., 2020). Returning crop residue can also reduce the depletion of organic carbon in the soil (Ma et al., 2021). According to Zhao et al. (2019), incorporating straw and partial fertilizers resulted in a notable average increase of 64% in soil available nitrogen at depths of 0–20 cm. However, crop residues tend to possess a relatively high C/N ratio (ranging from 60–100:1). Consequently, the influx of these residues may prompt nitrogen immobilization, potentially necessitating additional nitrogen fertilizer usage (Fontaine et al., 2020). Even when the C/N ratio is lower, plant residues with a C/N ratio above 40 exhibits slower mineralization compared to those with a lower ratio. The suggested optimum C/N ratio typically falls between 35 and 40 (Shi, 2013).

The utilization of various organic residues or a combination of mineral and organic fertilizers has been associated with increased availability of macronutrients and reduced electrical conductivity in soil (Agegnehu et al., 2014; Hasnain et al., 2020; Mehdi et al., 2018). These practices commonly result in enhanced soil fertility (Ghosh & Devi, 2019; Mehdi et al., 2018). Across numerous analyzed studies, there's a consistent trend indicating a reduction in BD due to the application of different organic residues (Zhao et al., 2019; Al-Suhaibani et al., 2020; Ghosh & Devi, 2019; Kheir et al., 2021). Bulk density reduction with both types of residue incorporation and overseason is attributed to higher OM accumulation.

The observations from the fourth season, characterized by elevated SW content, increased soil OM, and reduced BD following successive wheat and maize crop cycles, suggest that the benefits of residue incorporation can accumulate over time. This is consistent with the concept of residue incorporation contributing to long-term soil health improvement, emphasizing its role in sustainable land management strategies. The PCA results indicated that soil chemical properties (TN, AP, AK, OM), soil physical properties (BD, water content), and agronomic traits (grain yield, stover yield, 1000-grain weight) are the key factors influencing crop yield.

The positive correlation between soil variables and yield can be due to that when crop residues are recycled in soil, the availability of N, P, K, and OM increases (Ali et al., 2020), reducing nutrient losses (Rasool et al., 2020), and enhancing crop yield.

The linear model, developed using multiple linear regression (MLR), and the non-linear model, built with artificial neural networks (ANN), was designed to predict maize and wheat crop yields using actual yield data, soil properties, and meteorological information. Both models proved effective, but the ANN model performed better, providing more

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accurate predictions and explaining a higher percentage of yield variation. Thus, the ANN model is slightly more reliable for predicting crop yields based on soil and environmental factors. These metrics suggest that the ANN model performed better than the linear regression model, with slightly lower error rates and higher explained variance. The ANN model surpassed the regression model in accuracy, suggesting it is a viable alternative for yield prediction (Basir et al., 2021). For cherry coffee yields, the ANN model achieved an R^2 of 0.9524 and an RMSE of 0.0784 tons, highlighting its potential for accurate yield estimation (Kittichotsatsawat et al., 2022).

CONCLUSION

Our research supports the benefits of adding crop residues to eroded lands to enhance their productivity and maintain soil health. Both types of crop residues increased yield and improved the soil properties. Compared to the initial status of OM and TN in the fourth season, postharvest soil properties of both OM and TN increased. The BD was reduced in the fourth season to its initial status. However, maize residues showed higher yields due to higher nutrients and organic matter content. The significance of PC1 and PC2 across all seasons and crops highlights their role in understanding the intricate interactions between soil properties and agricultural outcomes. The relationship between agronomic traits and soil properties emphasizes the significance of soil health for food security. However, there are a number of variables, including the composition of residue, the prevailing climate and particularly soil properties that influence residue management. For the best possible results investigation of these dynamics and long-term field studies are required. The multiple linear regression model demonstrated accuracy and generalizability in our study’s predictive analysis. The artificial neural network model achieved high accuracy on both training and testing datasets and holds promise for practical applications in improving crop yield and soil properties through residue management.

Author Contributions

N. Afsar conducted the experiments, overseeing both data collection and analyses. N. Afsar wrote the manuscript. A. Shaheen designed the experiments and revised the manuscript. Both authors contributed to the final draft of the manuscript. Both authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethics Statement

This study was conducted on the experimental farm of the University of Poonch. No permission from local farmers was required, as the research was confined to the university's designated experimental area.

Conflict of interest

There is no conflict of interest.

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