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Effect of Humic Acid on Yield, Soil Nutrient Availibilty and Chemical Status after Harvest of Wheat

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Wheat (*Triticum aestivum* L.) is a major staple crop, but its productivity and soil sustainability are increasingly challenged by the excessive and imbalanced use of chemical fertilizers. Integrated Nutrient Management, including the use of humic acid, offers a promising approach to improve soil health, nutrient availability, and crop productivity under intensive cultivation systems. A field experiment was conducted during the *rabi* seasons of 2023–24 and 2024–25 at the Pulse Research Station, Anand Agricultural University, Vadodara, Gujarat, to assess the effect of humic acid on soil chemical properties and nutrient dynamics under wheat (*Triticum aestivum* L.) cultivation. The study was laid out in a randomized block design comprising ten treatments with varying levels of recommended dose of fertilizers (RDF) in combination with soil and foliar application of humic acid. The results indicated that post-harvest soil pH and electrical conductivity were not significantly affected by different treatments. Application of 100% RDF + humic acid @ 10 kg ha^{-1} (T_4) recording the significantly highest values of grain yield (5242 kg ha^{-1}), straw yield (6137 kg ha^{-1}), available nitrogen (308 kg ha^{-1}) and phosphorus (61.95 kg ha^{-1}) during 2023–24, 2024–

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25 and pooled analysis, respectively, remaining statistically comparable with T_3. In contrast, available potassium did not show significant variation across treatments. Application of humic acid significantly increased soil organic carbon content and DTPA-extractable micronutrients (Fe, Zn, Mn and Cu), with the highest concentrations observed under T_{10} (75% RDF + soil application of humic acid @ 15 kg ha^{-1} + foliar spray @ 0.2% humic acid), followed by T_7, may be attributed to the foliar application of humic acid, which enhances direct nutrient absorption and utilization by plants, thereby minimizing nutrient fixation and residual buildup in the soil. Overall, the results demonstrate that the combined application of humic acid and inorganic fertilizers significantly enhances wheat productivity, enriches soil organic carbon and improves nutrient availability, thereby promoting sustainable soil fertility management.

Keywords: Humic acid; wheat; fertilizer management; organic carbon; soil fertility.

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most widely grown cereal crops and is essential for meeting global food and nutritional demands. In India, it is an important rabi crop cultivated under a wide range of agro-climatic conditions because of its adaptability and high productivity. Wheat is a key contributor to the food supply and provides important nutrients such as carbohydrates, proteins and minerals. The increase in its production over time has mainly been due to improved varieties, better irrigation facilities and increased fertilizer application (FAO, 2022; Shendare et al., 2024).

However, excessive and unbalanced use of chemical fertilizers over the years has negatively affected soil health. This has resulted in reduced organic matter, lower nutrient efficiency and overall decline in soil quality. These concerns highlight the importance of adopting sustainable nutrient management practices. Integrated Nutrient Management (INM), which combines chemical fertilizers with organic sources, is considered an effective method for improving soil fertility and sustaining crop yields (Canellas *et al.*, 2015). Despite the recognized benefits of humic acid and integrated nutrient management, region-specific evidence on their combined effects on soil nutrient dynamics remains limited, particularly with respect to micronutrient availability and soil organic carbon under intensive wheat cultivation. Additionally, variability in reported outcomes regarding optimal application rates and methods of humic acid highlights the need for further evaluation under diverse agro-climatic conditions.

Among organic inputs, humic acid has shown promising results due to its beneficial effects on both soil and plant growth. It helps improve soil structure, increases water-holding capacity and supports microbial activity. In addition, humic acid enhances nutrient availability by forming complexes with essential elements, which reduces nutrient losses and improves their uptake by plants (Canellas and Olivares, 2014). Thus, combining humic acid with recommended fertilizer practices can be an effective approach to increase wheat productivity while maintaining soil health over the long term.

2. Materials and Methods

A field experiment was conducted during the *rabi* seasons of 2023–24 and 2024–25 at the Pulse Research Station, Anand Agricultural University, Vadodara, Gujarat, India, located in the middle Gujarat agro-climatic zone characterized by a semi-arid climate. The experimental soil was loamy sand (Goradu), slightly alkaline in reaction with low electrical conductivity. It was deficient in organic carbon and available nitrogen, while medium in available phosphorus, potassium and micronutrient status. The experiment was laid out in a randomized block design (RBD) comprising ten treatments with three replications. The treatments consisted of different levels of recommended dose of fertilizers (RDF: 120-60-40 kg N-P_2O_5-K_2O ha^{-1}) combined with soil and foliar application of humic acid: T_1: Absolute Control, T_2: 100% RDF. Soil application of humic acid treatments (T_3: 100% RDF + Soil application of humic acid @ 5 kg/ha, T_4: 100% RDF + Soil application of humic acid @ 10 kg/ha, T_5: 75% RDF + Soil application of humic acid @ 5 kg/ha, T_6: 75% RDF + Soil application of humic acid @ 10 kg/ha), Soil and foliar of application of humic acid treatments (T_7: 75% RDF + Soil application of humic acid @ 15 kg/ha, T_8: T_5 + Foliar application of humic acid @ 0.2% (30 & 45 DAS), T_9: T_6 + Foliar application of humic acid @ 0.2% (30 & 45 DAS), T_{10}: T_7 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)). The experimental crop was wheat (*Triticum aestivum* L.) cv. GW 451, a variety well adapted to the agro-climatic conditions of the region. Sowing was performed using the line sowing method with a row spacing of 22.5 cm to maintain optimum plant population and ensure efficient utilization of resources. The crop was managed following recommended agronomic practices. Nitrogen was applied in split doses, whereas the entire quantity of phosphorus and potassium was applied as a basal dose at the time of sowing. Grain yield, straw yield and soil parameters were analysed using standard analytical procedures.

3. Results and Discussion

3.1 Soil pH and EC

Application of humic acid at different levels along with RDF had no significant effect on soil pH and electrical conductivity (EC) after harvest of wheat, either during individual years or in the pooled analysis, indicating no change in soil reaction and salinity (Table 1).

3.2 Organic Carbon

Soil organic carbon content after wheat harvest was significantly influenced by the integrated application of humic acid with different levels of RDF. The highest SOC was observed under T_{10} (75% RDF + soil application of humic acid @ 15 kg ha^{-1} + 0.2% foliar application of humic acid), registering 7.93, 8.07 and 8.00 g kg^{-1} during 2023–24, 2024–25 and pooled analysis, respectively, which remained statistically at par with T_7 (75% RDF + humic acid @ 15 kg ha^{-1}). The significantly lowest OC content (3.33 g kg^{-1}) in pooled analysis was recorded under control (T_1). These findings are in agreement with Kumar and Singh (2017) and Thakur *et al.* (2017), who also reported increased soil organic carbon with integrated application of humic acid and fertilizers in wheat. The improvement in organic carbon may be attributed to the carbon-rich nature of humic acid and its role in forming stable organo-mineral complexes, which reduce decomposition losses. It also enhances microbial activity and root growth, leading to greater biomass addition and residue incorporation. Application of humic acid through foliar spray led to a marked improvement in soil organic carbon, reflecting enhanced biomass production and subsequent organic matter addition. Higher OC under combined soil and foliar application may be due to improved crop growth, resulting in increased root biomass and rhizodeposition (Table 2).

3.3 Available Nitrogen

Available nitrogen in soil after wheat harvest was significantly influenced by humic acid application along with RDF during both years and in pooled analysis. Treatment T_4 (100% RDF + soil application of humic acid @ 10 kg ha^{-1}) recorded the significantly highest available nitrogen (305, 311 and 308 kg ha^{-1} in 2023–24, 2024–25 and pooled, respectively) and remained statistically at par with T_3. The increase in available nitrogen may be attributed to enhanced mineralization, improved nutrient retention and stimulated microbial activity due to humic acid. These findings corroborate earlier reports by Kumar *et al.* (2021), Pidurkar *et al.* (2022) and Kumar *et al.* (2023) (Table 3).

3.4 Available Phosphorus

Available phosphorus content in soil after harvest showed significant variation due to humic acid application across both years and pooled analysis. The significantly highest phosphorus availability was recorded under T_4 (100% RDF + soil application of humic acid @ 10 kg ha^{-1}) with values 61.35, 62.55 and 61.95 kg ha^{-1} in 2023–24, 2024–25 and pooled, respectively, whereas the lowest values were observed under control (T_1). The increased phosphorus availability may be attributed to reduced fixation through complexation of Ca, Fe, and Al ions, enhancing P solubility. These observations are in agreement with Thakur *et al.* (2017), Kumar *et al.* (2021) and Pidurkar *et al.* (2022).

3.5 Available Potassium

Soil available potassium after wheat harvest was not significantly influenced by humic acid application along with RDF during 2023–24 and 2024–25. However, pooled results indicated the significantly highest K_2O (161.00 kg ha^{-1}) under T_{10} (75% RDF + soil application of humic acid @ 15 kg ha^{-1} + foliar application @ 0.2% of humic acid), which remained statistically at par with T_3 to T_9. The improved potassium availability may be attributed to humic acid-induced dissolution of K-bearing minerals, reduced fixation through interlayer blocking

Table 1. Effect of humic acid on soil pH and EC after harvest of wheat

Tr. No.	Treatment details	Soil pH			EC (dS m^{-1})		
		Initial : 8.09			Initial : 0.34		
		2023–24	2024–25	Pooled	2023–24	2024–25	Pooled
T_1	Absolute control	8.05	8.02	8.03	0.32	0.31	0.31
T_2	100% RDF	8.04	8.02	8.03	0.33	0.31	0.32
T_3	100% RDF + Soil application of humic acid @ 5 kg/ha	8.03	7.95	7.99	0.31	0.30	0.30
T_4	100% RDF + Soil application of humic acid @ 10 kg/ha	8.00	7.92	7.96	0.33	0.32	0.33
T_5	75% RDF + Soil application of humic acid @ 5 kg/ha	8.00	7.85	7.93	0.34	0.33	0.33
T_6	75% RDF + Soil application of humic acid @ 10 kg/ha	8.03	7.86	7.95	0.33	0.32	0.33
T_7	75% RDF + Soil application of humic acid @ 15 kg/ha	8.03	7.72	7.88	0.30	0.30	0.30
T_8	T_5 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	8.02	8.00	8.01	0.33	0.32	0.33
T_9	T_6 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	8.08	7.95	8.02	0.32	0.31	0.31
T_{10}	T_7 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	8.06	7.99	8.02	0.29	0.30	0.30
T	S S.Em±	0.25	0.28	0.19	0.02	0.01	0.01
	C CD (P=0.05%)	NS	NS	NS	NS	NS	NS
Y	S. S.Em±	-	-	0.08	-	-	0.00
	C. CD (P=0.05%)	-	-	NS	-	-	NS
Y X T	S. S.Em±	-	-	0.26	-	-	0.01
	C. CD (P=0.05%)	-	-	NS	-	-	NS
C. CV.%		5.40	6.06	5.73	8.20	8.11	8.16

Table 2. Effect of humic acid on organic carbon and available nitrogen after harvest of wheat

Tr. No.	Treatment details	Organic carbon (g kg^{-1})			Available Nitrogen (kg ha^{-1})		
		Initial : 1.32			Initial : 193.7		
		2023–24	2024–25	Pooled	2023–24	2024–25	Pooled
T_1	Absolute control	3.27	3.40	3.33	199	203	201
T_2	100% RDF	4.13	4.20	4.17	258	264	261
T_3	100% RDF + Soil application of humic acid @ 5 kg/ha	6.43	6.57	6.50	282	286	284
T_4	100% RDF + Soil application of humic acid @ 10 kg/ha	6.93	6.83	6.88	305	311	308
T_5	75% RDF + Soil application of humic acid @ 5 kg/ha	6.77	6.67	6.72	247	250	249
T_6	75% RDF + Soil application of humic acid @ 10 kg/ha	7.03	7.07	7.05	253	256	255
T_7	75% RDF + Soil application of humic acid @ 15 kg/ha	7.53	7.77	7.65	265	271	268
T_8	T_5 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	6.80	6.93	6.87	251	259	255

Tr. No.	Treatment details	Organic carbon (g kg^{-1})			Available Nitrogen (kg ha^{-1})		
		Initial : 1.32			Initial : 193.7		
		2023–24	2024–25	Pooled	2023–24	2024–25	Pooled
T_9	T_6 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	7.10	7.20	7.15	261	270	265
T_{10}	T_7 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	7.93	8.07	8.00	272	274	273
T	S.Em±	0.27	0.29	0.20	11.14	12.16	8.24
	CD (P=0.05%)	0.81	0.85	0.56	33.09	36.13	23.65
Y	S.Em±	-	-	0.09	-	-	3.69
	CD (P=0.05%)	-	-	NS	-	-	NS
Y X T	S.Em±	-	-	0.28	-	-	11.66
	CD (P=0.05%)	-	-	NS	-	-	NS
C.V.%		7.36	7.64	7.50	7.44	7.97	7.71

Table 3. Effect of humic acid on available phosphorus and potash after harvest of wheat

Tr. No.	Treatment details	P_2O_5 (kg ha^{-1})			K_2O (kg ha^{-1})		
		Initial : 38.0			Initial : 178		
		2023–24	2024–25	Pooled	2023–24	2024–25	Pooled
T_1	Absolute control	33.50	33.64	33.57	124.33	128.00	126.17
T_2	100% RDF	46.51	46.84	46.67	143.67	144.67	144.17
T_3	100% RDF + Soil application of humic acid @ 5 kg/ha	55.28	55.51	55.40	155.00	157.00	156.00
T_4	100% RDF + Soil application of humic acid @ 10 kg/ha	61.35	62.55	61.95	157.33	159.67	158.50
T_5	75% RDF + Soil application of humic acid @ 5 kg/ha	47.46	47.50	47.48	146.00	148.33	147.17
T_6	75% RDF + Soil application of humic acid @ 10 kg/ha	49.10	49.57	49.34	151.33	152.00	151.67
T_7	75% RDF + Soil application of humic acid @ 15 kg/ha	52.38	52.50	52.44	157.67	157.29	157.48
T_8	T_5 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	47.01	48.12	47.56	152.00	153.67	152.83
T_9	T_6 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	50.29	50.95	50.62	153.67	155.33	154.50
T_{10}	T_7 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	53.49	54.10	53.80	160.00	162.00	161.00
T	S.Em±	2.03	2.36	1.56	7.19	6.45	4.83
	CD (P=0.05%)	6.03	7.01	4.46	NS	NS	13.85
Y	S.Em±	-	-	0.70	-	-	2.16
	CD (P=0.05%)	-	-	NS	-	-	NS
Y X T	S.Em±	-	-	2.20	-	-	6.83
	CD (P=0.05%)	-	-	NS	-	-	NS
C.V.%		7.09	8.15	7.64	8.29	7.36	7.84

Table 4. Effect of humic acid on DTPA-extractable Iron and Manganese concentration after harvest of wheat

Tr. No.	Treatment details	Iron (mg kg^{-1})			Manganese (mg kg^{-1})		
		Initial : 5.90			Initial : 6.57		
		2023–24	2024–25	Pooled	2023–24	2024–25	Pooled
T_1	Absolute control	4.80	5.13	4.97	6.32	6.35	6.34
T_2	100% RDF	5.47	5.77	5.62	7.03	7.12	7.08
T_3	100% RDF + Soil application of humic acid @ 5 kg/ha	6.27	6.33	6.30	7.83	7.87	7.85
T_4	100% RDF + Soil application of humic acid @ 10 kg/ha	7.10	7.17	7.13	9.11	9.34	9.23
T_5	75% RDF + Soil application of humic acid @ 5 kg/ha	6.23	6.60	6.42	7.76	7.81	7.79
T_6	75% RDF + Soil application of humic acid @ 10 kg/ha	7.13	7.17	7.15	8.92	8.99	8.95
T_7	75% RDF + Soil application of humic acid @ 15 kg/ha	8.03	8.07	8.05	10.41	11.16	10.79
T_8	T_5 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	6.73	6.90	6.82	9.72	9.92	9.82
T_9	T_6 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	7.23	7.30	7.27	10.29	10.72	10.50
T_{10}	T_7 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	8.13	8.20	8.17	11.33	11.89	11.61
T	S.Em±	0.24	0.30	0.19	0.32	0.38	0.25
	CD (P=0.05%)	0.72	0.88	0.55	0.95	1.14	0.72
Y	S.Em±	-	-	0.09	-	-	0.11
	CD (P=0.05%)	-	-	NS	-	-	NS
Y X T	S.Em±	-	-	0.27	-	-	0.35
	CD (P=0.05%)	-	-	NS	-	-	NS
C.V.%		6.28	7.45	6.90	6.25	7.27	6.80

Table 5. Effect of humic acid on DTPA-extractable Zinc and Copper concentration after harvest of wheat

Tr. No.	Treatment details	Zinc (mg kg^{-1})			Copper (mg kg^{-1})		
		Initial : 0.88			Initial : 1.40		
		2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
T_1	Absolute control	0.60	0.63	0.60	0.63	0.60	0.63
T_2	100% RDF	0.78	0.83	0.78	0.83	0.78	0.83
T_3	100% RDF + Soil application of humic acid @ 5 kg/ha	1.21	1.26	1.21	1.26	1.21	1.26
T_4	100% RDF + Soil application of humic acid @ 10 kg/ha	1.37	1.43	1.37	1.43	1.37	1.43
T_5	75% RDF + Soil application of humic acid @ 5 kg/ha	1.20	1.28	1.20	1.28	1.20	1.28
T_6	75% RDF + Soil application of humic acid @ 10 kg/ha	1.36	1.40	1.36	1.40	1.36	1.40
T_7	75% RDF + Soil application of humic acid @ 15 kg/ha	1.54	1.61	1.54	1.61	1.54	1.61

Tr. No.	Treatment details	Zinc (mg kg^{-1})			Copper (mg kg^{-1})		
		Initial : 0.88			Initial : 1.40		
		2023–24	**2024–25**	**2023–24**	**2024–25**	**2023–24**	**2024–25**
T_8	T_5 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	1.36	1.38	1.36	1.38	1.36	1.38
T_9	T_6 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	1.47	1.51	1.47	1.51	1.47	1.51
T_{10}	T_7 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	1.70	1.79	1.70	1.79	1.70	1.79
T	S.Em±	0.06	0.07	0.06	0.07	0.06	0.07
	CD (P=0.05%)	0.17	0.19	0.17	0.19	0.17	0.19
Y	S.Em±	-	-	-	-	-	-
	CD (P=0.05%)	-	-	-	-	-	-
Y X T	S.Em±	-	-	-	-	-	-
	CD (P=0.05%)	-	-	-	-	-	-
C.V.%		7.86	8.60	8.26	7.46	6.37	6.91

Table 6. Effect of humic acid on grain and straw yield of wheat

Tr. No.	Treatment details	Grain Yield (kg ha^{-1})			Straw Yield (kg ha^{-1})		
		2023–24	**2024–25**	**Pooled**	**2023–24**	**2024–25**	**Pooled**
T_1	Absolute control	2413	2443	2428	3197	3210	3203
T_2	100% RDF	4240	4297	4268	5283	5277	5280
T_3	100% RDF + Soil application of humic acid @ 5 kg/ha	4657	4747	4702	5827	5787	5807
T_4	100% RDF + Soil application of humic acid @ 10 kg/ha	5200	5283	5242	6120	6153	6137
T_5	75% RDF + Soil application of humic acid @ 5 kg/ha	4263	4293	4278	5093	5107	5100
T_6	75% RDF + Soil application of humic acid @ 10 kg/ha	4337	4383	4360	5167	5173	5170
T_7	75% RDF + Soil application of humic acid @ 15 kg/ha	4448	4497	4473	5243	5277	5260
T_8	T_5 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	4297	4310	4303	5170	5150	5160
T_9	T_6 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	4360	4450	4405	5227	5297	5262
T_{10}	T_7 + Foliar application of humic acid @ 0.2% (30 & 45 DAS)	4487	4543	4515	5337	5373	5355
T	S.Em±	237	248	171	262	260	185
	CD (P=0.05%)	704	735	491	778	774	530
Y	S.Em±	-	-	76.6	-	-	82.5
	CD (P=0.05%)	-	-	NS	-	-	NS
Y X T	S.Em±	-	-	242	-	-	261
	CD (P=0.05%)	-	-	NS	-	-	NS
C.V.%		9.61	9.91	9.76	8.78	8.71	8.74

and increased adsorption of K^+ ions. Foliar application of humic acid functions as a fast-acting organic biostimulant that enhances nutrient uptake, promotes photosynthetic efficiency, and improves plant tolerance to abiotic stresses. Similar findings have been reported by Haranal *et al.* (2023) and Kumar *et al.* (2023).

3.6 DTPA-extractable Micronutrients (Fe, Zn, Mn and Cu)

DTPA-extractable Fe, Zn, Mn, and Cu were significantly influenced by the integrated use of humic acid and RDF across both years and in pooled analysis. The lowest Fe (4.97 mg kg^{-1}) and Mn (6.34 mg kg^{-1}) were recorded under control (T_1), while the significantly highest values were observed under T_{10} (75% RDF + soil application of humic acid @ 15 kg ha^{-1} + 0.2% foliar spray of humic acid), recording Fe (8.17 mg kg^{-1}) and Mn (11.61 mg kg^{-1}). Treatment T_7 (75% RDF + humic acid @ 15 kg ha^{-1}) remained statistically at par with T_{10}. Similarly, Zn (1.74 mg kg^{-1}) and Cu (2.57 mg kg^{-1}) were significantly higher under T_{10}, followed by T_7.

The improvement in micronutrient availability may be attributed to the chelating effect of humic acid. Enhanced availability of Fe and Mn with humic acid application is mainly attributed to its chelating action, which forms stable organo-metal complexes and prevents oxidation and precipitation losses. It also stimulates microbial activity and root exudation, thereby increasing organic ligands and micronutrient solubilization. Foliar-applied humic acid serves as a rapid biostimulant, significantly enhancing nutrient assimilation, optimizing photosynthetic performance and strengthening plant defense mechanisms against environmental stresses. Increased Zn and Cu availability is linked to the formation of soluble humate complexes, reduced fixation, improved soil conditions, and lowered rhizosphere pH. These results are in close agreement with Mackowiak *et al.* (2001), Kumar and Singh (2017) and Kumar *et al.* (2024).

3.7 Yield of Wheat

Both grain and straw yields were significantly influenced by the application of humic acid in conjunction with fertilizers (Table 6). The treatment receiving 100% recommended dose of fertilizers (RDF) along with soil application of humic acid @ 10 kg ha^{-1} recorded the highest grain yield (5200, 5283 and 5242 kg ha^{-1} during 2023–24, 2024–25 and on pooled basis, respectively), and was found to be significantly superior over other treatments, though it remained statistically at par with T_3. The lowest grain yield was observed under the control (T_1). The enhancement in grain yield may be attributed to improvement in soil physico-chemical properties, increased nutrient availability and use efficiency, enhanced vegetative growth and tillering, and higher photosynthetic activity, which collectively contributed to greater assimilate translocation towards the grains. These findings are in agreement with the results reported by Khan *et al.* (2018), Chaubey *et al.* (2025) and Izquierdo *et al.* (2025).

A similar trend was observed in straw yield (Table 6). The highest straw yield (6120, 6153 and 6137 kg ha^{-1} during 2023–24, 2024–25 and pooled analysis, respectively) was recorded under the application of 100% RDF + humic acid @ 10 kg ha^{-1}, followed by T_3. The increase in straw yield can be attributed to improved soil fertility status, enhanced nutrient uptake, and better growth attributes such as plant height, number of tillers, and dry matter accumulation. These results corroborate the findings of Chaubey *et al.* (2025).

4. Conclusion

The results of this study concludes that application of humic acid along with RDF significantly enhances yield of wheat and improves nutrient availability in soil. The treatment with 100% RDF + soil application of humic acid @ 10 kg ha^{-1} recorded the highest yield of wheat as well as available nitrogen and phosphorus in soil. In addition, the use of 75% RDF combined with soil application of humic acid @ 15 kg ha^{-1} along with 0.2% foliar spray improved organic carbon and available micronutrient status in soil, can be attributed to the direct absorption and efficient utilization of nutrients through the foliage. Therefore, the integrated use of humic acid with inorganic fertilizers can be considered an effective and sustainable nutrient management strategy for wheat cultivation.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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