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Effects of poultry manure and seaweed extract on growth and yield of wheat (*Triticum aestivum* L.)

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Abstract

The continuous use of chemical fertilisers has adversely affected soil condition and reduced the efficiency of nutrient use, resulting in lower wheat yields over time. A field study was performed during the rabi season of 2024–25 at the Agricultural Research Farm, Lovely Professional University, Punjab, using a split-plot design, with four levels of poultry manure (PM) (0, 5, 10 and 15 tonnes per hectare (t ha^{-1})) as main plot treatments and four levels of seaweed extract (SE) (0, 0.25 %, 0.75 % and 1 %) as subplot treatments, forming 16 treatment combinations with 3 replications. The study showed that applying PM at 15 t ha^{-1} significantly enhanced growth parameters including plant height, number of tillers and dry matter accumulation, while seaweed extract at 1 % enhanced crop vigour. The integrated application of 15 t ha^{-1} poultry manure and 1 % SE recorded the highest grain yield (61.21 quintals per hectare (q ha^{-1})), straw yield (56.09 q ha^{-1}) and harvest index (52.21 %), with a significant interaction between poultry manure and SE ($p < 0.05$). These findings indicate a synergistic effect between PM and SE. The use of organic manure combined with biostimulants significantly enhanced yield attributes such as spike length and grain formation, leading to higher wheat productivity. This study indicates that the use of PM along with SE can be considered as an environmentally friendly approach for improving yield in wheat cultivation.

Keywords: agronomic performance; biostimulants; crop productivity; nutrient-use efficiency; organic amendments; soil fertility

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Introduction

Wheat (*Triticum aestivum* L.) is one of the major cereal crops cultivated globally and a member of the Poaceae family. It is one of the top staple foods for millions of people and serves as one of the primary sources of daily carbohydrates, protein, vitamins and minerals. Being a major food contributor to international food security, wheat supplies about 20–40 % of the calories in most nations, making it one of the top three globally cultivated crops (1, 2). Due to rapid population growth and increasing pressure on agricultural land, the global demand for wheat has been continuously increasing every year. The demand for wheat is increasing and therefore, there is a need to improve its productivity through suitable nutrient management practices, particularly under changing climatic conditions and declining soil fertility (3–5). Nutrient management has an important role in maintaining wheat productivity. Integrated nutrient management can be used to reduce the dependence on chemical fertilisers by making use of both organic and other nutrient sources. Poultry manure (PM) is one of the organic sources that can supply nitrogen (N), phosphorus (P), potassium (K) and micronutrients to the crop. It also adds organic matter to the soil and may improve soil structure, water-holding capacity and microbial activity. Several studies have also claimed that PM improves plant height, tillering, biomass production and yield, primarily due to its slow-release nutrients that enhance soil health (6). Seaweed extract (SE) is another input that has been used to improve crop growth. It contains plant hormones, amino acids, vitamins and antioxidants, which can have beneficial effects on plant growth and development. Application of SE may improve root growth, chlorophyll formation, nutrient uptake and other physiological activities of the plant. It may also help crops to tolerate stress and improve grain production. Such effects have been reported in different crops, including wheat (7–9).

Although both PM and SE have shown promising results independently, limited research exists regarding their integrated effects on PM and SE, particularly under North Indian rabi season conditions. Previous studies have examined the effects of these inputs separately, whereas information on their combined application and possible interaction under the agro-climatic conditions of North India is still limited. This study was conducted to assess how different concentrations of PM and SE impact the growth and yield characteristics of wheat, both individually and in combination. The integration of organic manure with a biostimulant can provide balanced nutrient management

by improving soil fertility as well as plant physiological activity. It was hypothesised that the combined application of PM and SE would promote wheat growth and yield more effectively than their individual application. The objective of the experiment is to evaluate the individual effects of PM and SE and their interaction effects on growth, yield and economics of the crop. The goal of the experiment was to identify the optimal combination for enhancing wheat performance under field conditions and to provide viable options for nutrient management in future wheat production.

Materials and Methods

The field study was carried out in the rabi season of 2024 –25 at the Agriculture Research Farm, Lovely Professional University, Punjab, which is located 252 m above sea level at latitude 31°14'39.10" N and longitude 75°41'51.67" E. The study area experiences a humid subtropical climate with hot temperatures during summer and cold temperatures in winter and 500–700 mm of annual rainfall, most of which falls during the south-west monsoon. The average temperature during the crop growth period was between 25 °C and 35 °C, which made it ideal for growing wheat. Since the experiment was conducted during only one rabi season (2024–25), variations in seasonal weather conditions may have affected wheat growth and its response to nutrient application. Therefore, the results are mainly applicable to similar agro-climatic conditions of North India and should be further validated through experiments conducted over multiple seasons and locations. Soil texture (sandy loam) was assessed using the hydrometer method (10). Soil pH was measured with a glass electrode pH meter in a 1 : 2.5 soil–water suspension (11). Soil samples were collected from the 0–15 cm depth prior to sowing, air-dried and sieved using a 2 mm mesh and analysed for basic physicochemical properties following standard laboratory procedures. The soil of the study area was observed to be slightly alkaline in reaction and the available N was determined using the alkaline permanganate method (12). Available P was estimated using Olsen's sodium bicarbonate extraction method (13). Available K was extracted with neutral normal ammonium acetate solution and estimated using a flame photometer. Soil samples were randomly collected from various locations of the field using a soil auger to obtain a representative sample. The recommended fertiliser dose of 120 : 60 : 40 kg ha^{-1} of N : P_2O_5 : K_2O was applied uniformly to all treatments in two split doses, with the first dose applied as a basal application at the time of sowing and the second dose applied at the appropriate crop growth stage. Poultry manure treatments were imposed in addition to the recommended NPK fertiliser dose and did not replace any portion of the recommended fertiliser dose. The field experiment was conducted using a split-plot design consisting of four poultry manure treatments in the main plots and four seaweed extract treatments in the subplots. Each plot measured 5 × 3 m. Randomisation was carried out in two stages, with the PM treatments first assigned randomly to the main plots, followed by random assignment of the seaweed extract treatments to the subplots within each main plot (Fig. 1). The PM treatments included M_1: Control, M_2: 5 t ha^{-1}, M_3: 10 t ha^{-1} and M_4: 15 t ha^{-1}. The SE treatments consisted of S_1: control, S_2: 0.25 %, S_3: 0.75 % and S_4: 1 %.

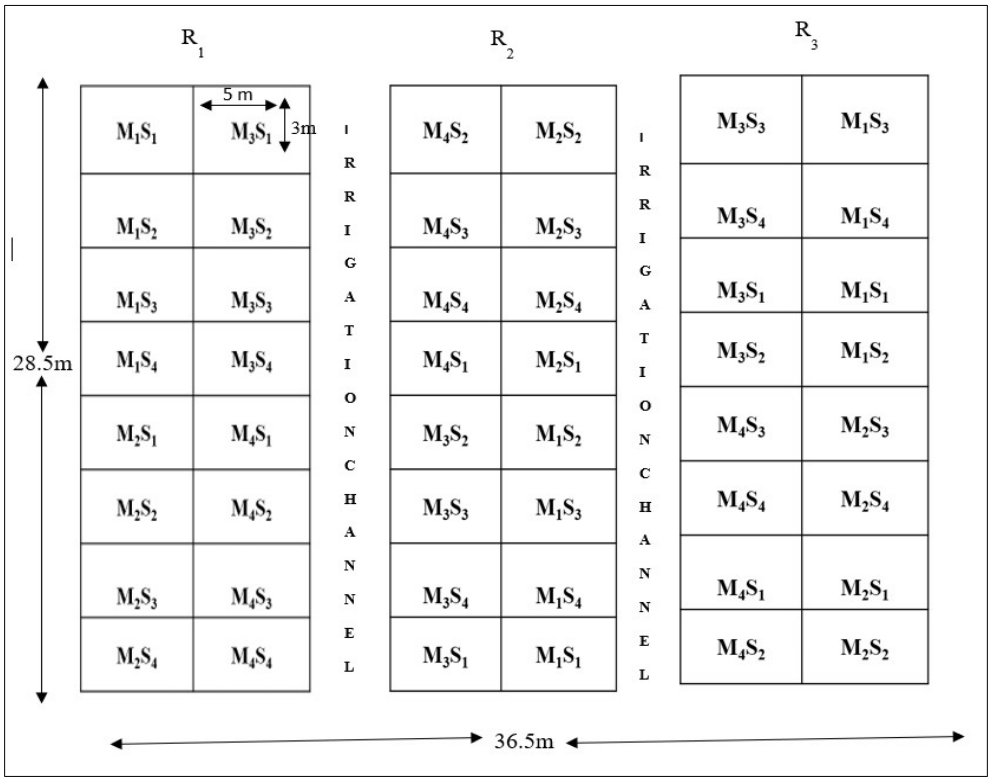


Fig. 1. Layout of experimental field.

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The PBW-824 wheat variety was drilled with a row spacing of 20 cm. The PM used in the experiment contained approximately 2.64 % N, 2.21 % P_2O_5 and 1.16 % K_2O. Poultry manure was applied to the respective plots by broadcasting it at the prescribed rates, 15 days before sowing. After application, the manure was incorporated well into the soil to obtain an even distribution across the plots. A commercially available liquid SE (Jaivizyme seaweed) was used for the experiment. The concentrations were prepared by diluting the extract with water and applied as foliar sprays using a backpack sprayer at tillering and booting stages. To improve absorption and crop response, the foliar spray was applied during the tillering stage and repeated at the booting stage. The study's SE originated from brown marine algae (*Sargassum* spp.), which are well-known for their biostimulant qualities and capacity to boost plant physiological activity.

Weed management was conducted via manual weeding at 30 and 60 days after sowing (DAS) and irrigation was applied at least three times according to crop requirements. Harvesting was performed manually at maturity and the grains were threshed, cleaned and measured. Plant height was measured from the ground level to the tip of the plant at maturity and expressed in cm. Effective tillers were counted from a randomly selected area of 1 m² in each plot and expressed as number per square metre. Dry weight was recorded from a randomly selected 1 m² area in each plot and expressed as gram per square metre. Spikelets per spike and grains per spike were determined by counting the respective components from randomly selected spikes. Test weight was determined by weighing 1000 grains and expressed in grams. Grain and straw yields were recorded from the harvested area of 1 m² in each plot and converted to quintals per hectare (q ha^{-1}). Harvest index was calculated as the ratio of grain yield to biological yield and expressed as a percentage and the data were examined statistically using analysis of variance (ANOVA), with significance tested at 5 % critical difference (CD) and graphical representations were generated using graphical analysis of plant experiment data (GRAPES) 1.1.0 software.

$$\text{Harvest index (\%)} = \frac{\text{Economic yield (q ha}^{-1})}{\text{Bilological yield (q ha}^{-1})} \times 100 \quad (14)$$

$$\text{Benefit-cost ratio (B : C)} = \frac{\text{Gross return}}{\text{Cost of cultivation}} \quad (15)$$

Results and Discussion

Effects of poultry manure and seaweed extract on growth parameters of wheat

Growth attributes of wheat showed a gradual increase with increasing levels of poultry manure and SE (Table 1). Among the poultry manure treatments, the control (M_1) recorded the lowest plant height (73.13 cm), dry weight (719.01 g m^{-2}) and number of tillers (300.47 m^{-2}). The M_4 treatment (15 t ha^{-1} PM) resulted in the highest plant height (90.32 cm), dry weight (1084.50 g m^{-2}) and number of tillers (334.69 m^{-2}). This improvement is attributed to enhanced soil condition and improved root development, which supported better plant growth and biomass accumulation. The organic matter added through poultry manure can also improve soil structure and microbial activity, thereby enhance nutrient availability and create a favourable soil environment for root growth (16). Regarding SE, the control (S_1) recorded lower values, while S_4 (1 % SE) recorded higher growth values of plant height (84.56 cm), dry weight (948.17 g m^{-2}) and number of tillers (321.23 m^{-2}) as shown in Table 1. The increase in growth parameters can be associated with the action of bioactive components in SE, which enhance metabolic processes and improve carbon assimilation efficiency. Seaweed extract contains bioactive compounds such as cytokinins, auxins and betaines, which could enhance cell division, root initiation and other physiological responses, which may lead to better photosynthetic performance and stress tolerance in wheat (17). This improved growth with PM and SE is consistent with previous wheat studies, which found that organic fertilisers and seaweed-based fertilisers resulted in greater plant growth and tillering. Among the combined treatments, M_4S_4 (15 t ha^{-1} PM + 1 % SE) recorded the highest plant height (95.21 cm), dry weight (1176.92 g m^{-2}) and number of tillers (345.24 m^{-2}), as shown in Tables 2–4. The significant interaction between these two inputs indicates that the combination of PM and SE was more efficient in improving wheat growth than their individual application. Poultry manure provided nutrients gradually and improved the soil environment around the roots, while the SE further supported root activity and nutrient uptake and physiological processes. Their complementary effects may have improved nutrient acquisition and utilisation, resulting in the observed synergistic response (18).

Table 1. Response of wheat to poultry manure (PM) and seaweed extract (SE) in growth parameters

Treatment details	Plant height (cm) at harvest	Dry weight (g m^{-2}) at harvest	Number of tillers m^{-2}
Main plots			
M_1: Control	73.13	719.01	300.47
M_2: 5 t ha^{-1} PM	79.28	832.01	308.87
M_3: 10 t ha^{-1} PM	83.70	943.66	318.99
M_4: 15 t ha^{-1} PM	90.32	1084.50	334.69
SEd (±)	1.20	4.99	4.37
CD (p = 0.05)	2.94	12.21	10.68
Sub plots			
S_1: Control	78.73	847.84	311.06
S_2: 0.25 % SE	80.67	870.17	313.71
S_3: 0.75 % SE	82.47	913.00	317.01
S_4: 1 % SE	84.56	948.17	321.23
SEd (±)	0.55	1.95	1.28
CD (p = 0.05)	1.12	4.02	2.65
Interaction (M × S)			
SEd (±) CD (p = 0.05)	1.09 1.22	3.89 8.03	2.57 5.30

PM: poultry manure; SE: seaweed extract.

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Table 2. Interaction effect of poultry manure (PM) and seaweed extract (SE) on plant height of wheat

Poultry manure seaweed extract	Plant height (cm) at harvest					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	69.25	72.69	74.04	76.52	292.50	73.13
M_2: 5 t ha^{-1} PM	77.83	78.19	80.11	81.00	317.13	79.28
M_3: 10 t ha^{-1} PM	81.51	83.25	84.52	85.52	334.80	83.70
M_4: 15 t ha^{-1} PM	86.34	88.53	91.21	95.21	361.30	90.32
Mean	78.73	80.67	82.47	84.56		
			SEd (±)		CD (0.05)	
S at same level of M			1.09		2.25	
M at same or different level of S			1.53		3.15	

PM: poultry manure; M: main plot; S: sub plot.

Table 3. Interaction effect of poultry manure and seaweed extract on dry weight of wheat

Poultry manure seaweed extract	Dry weight (g m^{-2}) at harvest					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	680.26	705.26	730.26	760.25	2876.03	719.01
M_2: 5 t ha^{-1} PM	800.26	820.26	840.26	867.26	3328.04	832.01
M_3: 10 t ha^{-1} PM	895.26	926.56	964.58	988.23	3774.63	943.66
M_4: 15 t ha^{-1} PM	1015.57	1028.59	1116.92	1176.92	4338.00	1084.50
Mean	847.84	870.17	913.00	948.17		
			SEd (±)		CD (0.05)	
S at same level of M			3.89		8.04	
M at same or different level of S			6.02		**12.43**	

PM: poultry manure; M: main plot; S: sub plot.

Table 4. Interaction effect of poultry manure (PM) and seaweed extract (SE) on number of tillers per square metre of wheat

Poultry manure seaweed extract	Number of tillers per square metre					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	297.53	298.87	301.92	303.56	1201.87	300.47
M_2: 5 t ha^{-1} PM	306.55	308.32	309.34	311.25	1235.46	308.87
M_3: 10 t ha^{-1} PM	313.25	317.38	320.44	324.88	1275.96	318.99
M_4: 15 t ha^{-1} PM	326.93	330.25	336.35	345.24	1338.78	334.69
Mean	311.06	313.71	317.01	321.23	311.06	
			SEd (±)		CD (0.05)	
S at same level of M			2.57		5.30	
M at same or different level of S			4.90		**10.11**	

PM: poultry manure; M: main plot; S: sub plot.

Effects of poultry manure and seaweed extract on yield parameters of wheat

Wheat yield attributes improved with increasing levels of PM and SE (Table 5). The lowest values for yield attributes, including effective tillers, were recorded in the control treatment (M_1) (250.83 m^{-2}), spikelets/spike (15.01), grains/spike (32.50), test weight (43.41 g) and grain yield (30.50 q ha^{-1}), straw yield (43.99 q ha^{-1}), harvest index (40.92 %). In contrast, M_4 (15 t ha^{-1}) produced the highest effective tillers (277.47 m^{-2}), spikelets/spike (22.27), grains/spike (42.93), test weight (45.57 g), grain yield (56.45 q ha^{-1}), straw yield (55.65 q ha^{-1}) and harvest index (50.28 %). The improvement in yield parameters attributable to PM can be explained by its gradual nutrient release, increased soil organic carbon levels and enhanced soil structure. This created favourable conditions for assimilate partitioning and reproductive development (19, 20). Similarly, treatments involving SE showed better performance, while the control (S_1) recorded the lowest yield values of effective tillers (259.55 m^{-2}), spikelets/spike (17.34), grains/spike (35.96),

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test weight (44.16 g), grain yield (39.70 q ha^{-1}), straw yield (48.94 q ha^{-1}), harvest index (44.31 %). On the other hand, S_4 (1% SE) showed the highest results of effective tillers (267.30 m^{-2}), spikelets/spike (19.35), grains/spike (38.69), test weight (44.72 g), grain yield (45.22 q ha^{-1}), straw yield (50.95 q ha^{-1}) and harvest index (46.45 %). This improvement can be attributed to the use of SE, which contains natural growth regulators including cytokinins, betaines and auxins that promote better photosynthesis and grain filling (21, 22). The results are consistent with previous wheat experiments which have shown that the use of poultry manure and seaweed-based biostimulants is beneficial, but the effects might differ depending on application rate and agro-climatic factors. The integrated application of M_4S_4 (15 t ha^{-1} of PM + 1 % SE) recorded the highest yield components of effective tillers (285.58 m^{-2}), spikelets/spike (24.79), grains/spike (46.69), test weight (45.94 g), grain yield (61.21 q ha^{-1}), straw yield (56.09 q ha^{-1}) and harvest index (52.21 %) (Tables 6–12). The significant PM × SE interaction resulted in improved yield attributes and grain production compared with their individual applications. This may be due to better nutrient availability and utilisation, along with enhanced assimilate partitioning towards developing spikes and grains (22).

Effects of poultry manure and seaweed extract on benefit cost ratio of wheat

The cost of cultivation included the cost of seed, fertilisers, PM, SE, labour, irrigation, field preparation, intercultural operations, harvesting and threshing. Higher levels of PM gave the maximum grain yield and also increased the gross income, which shows that it is a good organic nutrient source for wheat cultivation. However, with increasing levels of PM, the cost of cultivation also increased, which reduced the benefit: cost (B : C) ratio. Although 15 t ha^{-1} PM produced a higher grain yield, the large quantity required may create practical difficulties in terms of manure availability, labour requirements for handling and application and transportation expenses, which could limit its adoption by farmers where manure is not readily available locally. In comparison, the 1 % SE treatment (T_4) recorded the highest B : C ratio (1.96) due to its relatively lower investment, as presented in Table 13. The combined treatments, such as M_4S_4, produced higher grain yields and net returns; however, the B : C ratio (1.80) was lower because of the increased cost of inputs. Thus, the economic performance of the treatments depended on the relationship between the additional cost of inputs and the returns obtained. Repeated application of PM may provide long-term benefits through improvements in soil fertility, organic matter and soil structure, which could partly compensate for its higher short-term cost. Overall, PM was more effective for increasing yield, whereas the application of SE alone was more economical and gave better returns per unit cost under field conditions (23).

Break-even analysis

The break-even yield was estimated by comparing the additional input cost with the prevailing market price of wheat grain to determine whether the yield advantage of each treatment was sufficient to recover the additional investment.

Table 5. Response of wheat to poultry manure (PM) and seaweed extract (SE) in yield parameters

Treatments details	Number of effective tillers m^{-2}	Number of spikelets/ spikes	Number of grains/spike	Test weight (g)	Grain yield (q ha^{-1})	Straw yield (q ha^{-1})	Harvest index (%)
Main plots							
M_1: Control	250.83	15.01	32.50	43.41	30.50	43.99	40.92
M_2: 5 t ha^{-1} PM	258.63	17.02	35.02	44.12	38.15	48.68	43.91
M_3: 10 t ha^{-1} PM	265.44	18.70	38.12	44.77	45.24	52.05	46.49
M_4: 15 t ha^{-1} PM	277.47	22.27	42.93	45.57	56.45	55.65	50.28
SEd (±)	4.60	0.42	0.87	0.06	1.00	0.21	0.44
CD (p = 0.05)	11.24	1.02	2.12	0.13	2.44	0.52	1.07
Sub plots							
S_1: Control	259.55	17.34	35.96	44.16	39.70	48.94	44.31
S_2: 0.25 % SE	261.23	17.72	36.51	44.34	41.35	49.84	44.90
S_3: 0.75 % SE	264.29	18.60	37.42	44.64	44.05	50.64	45.94
S_4: 1 % SE	267.30	19.35	38.69	44.72	45.22	50.95	46.45
SEd (±)	1.08	0.35	0.47	0.06	0.69	0.11	0.28
CD (p = 0.05)	2.22	0.72	0.97	0.13	1.43	0.23	0.57
Interaction (M × S)							
SEd(±)	2.15	0.70	0.94	0.13	1.39	0.23	0.55
CD (p = 0.05)	4.44	1.44	1.94	0.26	2.86	0.46	1.14

PM: poultry manure; M: main plot; S: sub plot.

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Table 6. Interaction effect of poultry manure (PM) and seaweed extract (SE) on number of effective tillers per square metre of wheat

Poultry manure seaweed extract	Number of effective tillers per square metre					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	248.35	250.46	251.26	253.26	1003.33	250.83
M_2: 5 t ha^{-1} PM	256.56	257.28	259.44	261.24	1034.51	258.63
M_3: 10 t ha^{-1} PM	262.37	264.26	266.03	269.10	1061.76	265.44
M_4: 15 t ha^{-1} PM	270.93	272.92	280.45	285.58	1109.88	277.47
Mean	259.55	261.23	264.29	267.30		
			SEd (±)		CD (0.05)	
S at same level of M			2.15		4.45	
M at same or different level of S			4.96		10.24	

PM: poultry manure; M: main plot; S: sub plot.

Table 7. Interaction effect of poultry manure (PM) and seaweed extract (SE) on number of spikelets/spikes

Poultry manure seaweed extract	Number of spikelets/spike					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	14.26	14.65	15.24	15.89	60.04	15.01
M_2: 5 t ha^{-1} PM	16.56	16.68	17.26	17.57	68.08	17.02
M_3: 10 t ha^{-1} PM	18.34	18.39	18.95	19.12	74.81	18.70
M_4: 15 t ha^{-1} PM	20.18	21.16	22.96	24.79	89.09	22.27
Mean	17.34	17.72	18.60	19.35		
			SEd (±)		CD (0.05)	
S at same level of M			0.70		1.45	
M at same or different level of S			0.74		**1.52**	

PM: poultry manure; M: main plot; S: sub plot.

Table 8. Interaction effect of poultry manure (PM) and seaweed extract (SE) on number of grains/spikes of wheat

Poultry manure seaweed extract	Number of grains/spikes					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	31.63	31.92	32.89	33.57	130.01	32.50
M_2: 5 t ha^{-1} PM	34.28	34.98	35.26	35.57	140.09	35.02
M_3: 10 t ha^{-1} PM	37.36	37.91	38.28	38.95	152.49	38.12
M_4: 15 t ha^{-1} PM	40.57	41.22	43.23	46.69	171.71	42.93
Mean	35.96	36.51	37.42	38.69		
			SEd (±)		CD (0.05)	
S at same level of M			0.94		1.95	
M at same or different level of S			1.19		2.46	

PM: poultry manure; M: main plot; S: sub plot.

Table 9. Interaction effect of poultry manure (PM) and seaweed extract (SE) on test weight (g) of wheat

Poultry manure seaweed extract	Test weight (g)					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	43.13	43.27	43.55	43.68	173.63	43.41
M_2: 5 t ha^{-1} PM	43.94	44.01	44.16	44.35	176.46	44.12
M_3: 10 t ha^{-1} PM	44.56	44.74	44.85	44.92	179.08	44.77
M_4: 15 t ha^{-1} PM	45.02	45.34	45.98	45.94	182.28	45.57
Mean	44.16	44.34	44.64	44.72		
			SEd (±)		CD (0.05)	
S at same level of M			0.09		0.26	
M at same or different level of S			0.09		**0.25**	

PM: poultry manure; M: main plot; S: sub plot.

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Table 10. Interaction effect of poultry manure (PM) and seaweed extract (SE) on grain yield (q ha^{-1}) of wheat

Poultry manure seaweed extract	Grain yield (q ha^{-1})					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	28.27	30.05	31.41	32.26	121.99	30.50
M_2: 5 t ha^{-1} PM	35.53	37.25	39.63	40.16	152.58	38.15
M_3: 10 t ha^{-1} PM	43.45	44.62	45.62	47.26	180.95	45.24
M_4: 15 t ha^{-1} PM	51.55	53.47	59.54	61.21	225.78	56.45
Mean	39.70	41.35	44.05	45.22		
			SEd (±)		CD (0.05)	
S at same level of M			1.39		2.87	
M at same or different level of S			1.56		**3.23**	

PM: poultry manure; M: main plot; S: sub plot.

Table 11. Interaction effect of poultry manure (PM) and seaweed extract (SE) on straw yield (q ha^{-1}) of wheat

Poultry manure seaweed extract	Straw yield (q ha^{-1})					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	42.52	43.81	44.71	44.92	175.96	43.99
M_2: 5 t ha^{-1} PM	47.13	48.18	49.61	49.79	194.72	48.68
M_3: 10 t ha^{-1} PM	51.29	51.75	52.16	52.99	208.19	52.05
M_4: 15 t ha^{-1} PM	54.82	55.61	56.07	56.09	222.60	55.65
Mean	48.94	49.84	50.64	50.95		
			SEd (±)		CD (0.05)	
S at same level of M			0.23		0.47	
M at same or different level of S			0.29		**0.60**	

PM: poultry manure; M: main plot; S: sub plot.

Table 12. Interaction effect of poultry manure (PM) and seaweed extract (SE) on harvest index (%) of wheat

Poultry manure seaweed extract	Harvest index (%)					
	S_1	**S_2**	**S_3**	**S_4**	**Total**	**Mean**
M_1: Control	39.93	40.69	41.26	41.80	165.98	40.92
M_2: 5 t ha^{-1} PM	42.98	43.60	44.41	44.65	170.08	43.91
M_3: 10 t ha^{-1} PM	45.86	46.30	46.66	47.14	172.35	46.49
M_4: 15 t ha^{-1} PM	48.46	49.01	51.44	52.21	178.04	50.28
Mean	44.31	44.90	45.94	46.45		
			SEd (±)		CD (0.05)	
S at same level of M			0.55		1.14	
M at same or different level of S			0.52		**1.17**	

PM: poultry manure; M: main plot; S: sub plot.

Table 13. Benefit cost ratio and economic analysis of poultry manure (PM) and seaweed extract (SE) treatments in wheat

Code	Treatments	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	B : C ratio	Break even q ha^{-1}
T_1	Control	41960.00	72362.67	30402.67	1.72	16.39
T_2	0.25 % seaweed extract (SE)	42062.00	76936.53	34874.53	1.83	16.43
T_3	0.75 % seaweed extract	42113.00	80409.60	38296.60	1.91	16.45
T_4	1 % seaweed extract	42164.00	82585.60	40421.60	1.96	16.47
T_5	5 t ha^{-1} poultry manure (PM)	56960.00	90956.80	33996.80	1.60	22.25
T_6	5 t ha^{-1} PM + 0.25% SE	57062.00	95368.53	38306.53	1.67	22.29
T_7	5 t ha^{-1} PM + 0.75% SE	57113.00	101461.33	44348.33	1.78	22.31
T_8	5 t ha^{-1} PM + 1% SE	57164.00	102818.13	45654.13	1.80	22.33

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T_9	10 t ha^{-1} poultry manure	71960.00	111232.00	39272.00	1.55	28.11
T_{10}	10 t ha^{-1} PM + 0.25% SE	72062.00	114227.20	42165.20	1.59	28.15
T_{11}	10 t ha^{-1} PM + 0.75% SE	72113.00	116787.20	44674.20	1.62	28.17
T_{12}	10 t ha^{-1} PM + 1% SE	72164.00	120985.60	48821.60	1.68	28.19
T_{13}	15 t ha^{-1} poultry manure	86960.00	131976.53	45016.53	1.52	33.97
T_{14}	15 t ha^{-1} PM + 0.25% SE	87062.00	136891.73	49829.73	1.57	34.01
T_{15}	15 t ha^{-1} PM + 0.75% SE	87113.00	152430.93	65317.93	1.75	34.03
T_{16}	15 t ha^{-1} PM + 1% SE	87164.00	156697.60	69533.60	1.80	34.05

PM: poultry manure; M: main plot; S: sub plot.

Principal component analysis

The principal component analysis (PCA) biplot indicated that principal component (PC) PC1 accounted for most of the variation among the measured traits (Fig. 2). It had an eigenvalue of 9.861 and explained 98.608 % of the total variance. In comparison, PC2 had an eigenvalue of 0.089 and accounted for 0.888 % of the variance. Together, PC1 and PC2 explained 99.496 % of the total variation. The traits showing positive loadings on PC1 were grain yield (0.318), dry weight (0.318), harvest index (0.318), effective tillers (0.317), test weight (0.317), plant height (0.316), number of tillers (0.316), spikelets per spike (0.316), grains per spike (0.316) and straw yield (0.310). The positive loadings of these traits indicate their association with the variation represented by PC1. This means that these yield-related traits were mainly responsible for differentiating the treatments, which is similar to recent studies that found yield attributes to be the major contributors in PCA of wheat genotypes (24, 25). Traits pointing in the same direction showed strong positive correlations, indicating that when one yield component increases, the others also tend to increase, an observation commonly reported in recent multivariate analyses of cereals (26, 27). Treatment combinations positioned on the positive side of PC1 (e.g., M_3S_3, M_3S_4, M_4S_2 and M_4S_4) were associated with higher values of these favourable yield characteristics, whereas combinations on the negative/left side (such as M_1S_1, M_1S_2 and M_2S_1) exhibited comparatively lower results. The overall findings of the PCA analysis clearly show that the yield-contributing traits were the important parameters that dominated the majority of the variation across all the treatments, supporting recent findings on the central role of these traits in wheat improvement research (28).

Path analysis

The relationship between the main agronomic traits of wheat and their overall contribution to grain yield and harvest index are illustrated in the path diagram (Fig. 3). Plant height is the first influencing factor, which has both direct and indirect effects on key growth attributes including dry weight, number of tillers and effective tillers. An increase in these characteristics enhances spike development, which results in more spikelets and grains per spike. These traits are important mediators in the formation of yield and vegetative growth. The traits displayed at the bottom of the diagram such as test weight, straw yield and grain yield are the final outcome traits which are influenced by the interactive effect of the previously mentioned growth and reproductive parameters. The relationship between these traits is very strong, implying that they cannot function independently. Instead, the enhancement in early vegetative characteristics tends to improve yield attributes, which enhance grain yield and harvest index. The diagram is a clear demonstration of a sequential progression of plant height contributing to vegetative growth, which in turn supports reproductive structures and ultimately leads to higher grain yield, as observed in recent path-analysis studies in wheat (29).

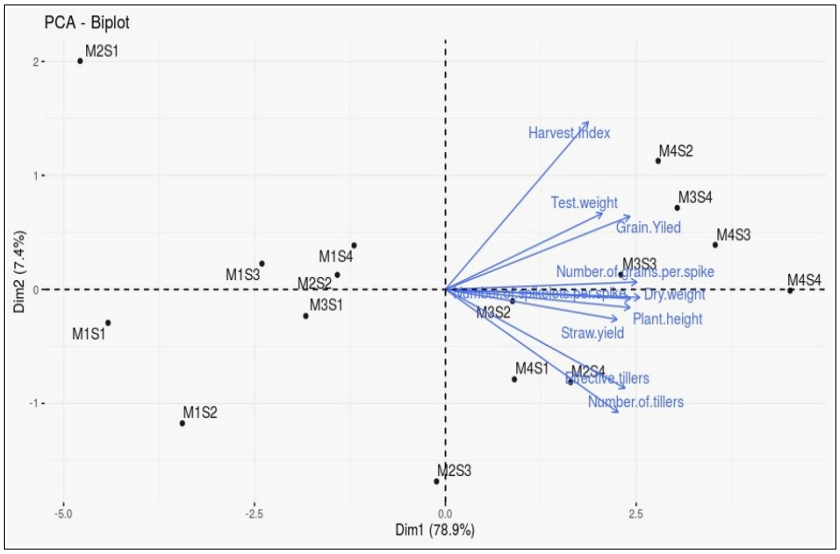


Fig. 2. Principal component analysis (PCA) biplot of growth and yield attributes in wheat.

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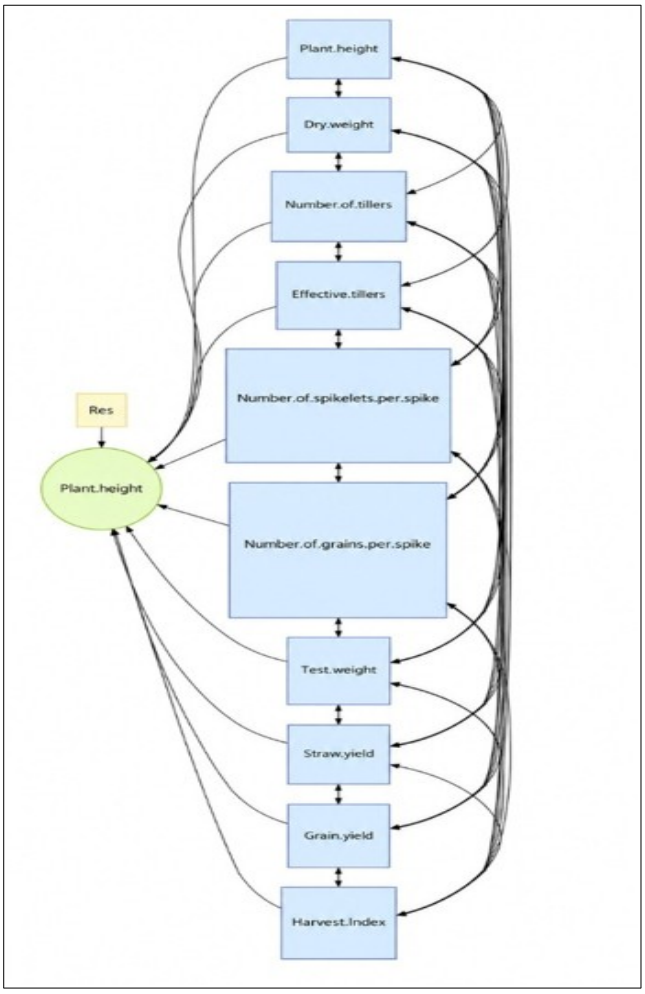


Fig. 3. Path coefficient analysis of wheat growth and yield parameter.

Conclusion

Wheat performed best under M_4 (15 t ha^{-1} poultry manure (PM)) with improved growth, tillering and grain yield among the main treatments, while S_4 (1 % seaweed extract (SE)) recorded the highest growth among sub-treatments due to natural hormones. The M_4S_4 combination produced the highest growth and grain yield due to synergistic effects. Economically, S_4 recorded the highest benefit-cost (B : C) ratio (1.96). Although M_4S_4 resulted in maximum gross and net returns, its B : C ratio (1.80) was lower due to the higher cost of PM. Based on the overall growth, yield and economic results, M_4S_4 (15 t ha^{-1} PM + 1 % SE) can be recommended for obtaining higher wheat productivity under similar agro-climatic conditions in North India, while considering the higher cost of inputs involved. However, further multi-season and multi-location studies are needed to confirm its long-term performance and economic feasibility.

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Authors' contributions

This research was a collaborative effort by MNR and KB, who jointly managed all aspects of the research, from conceptualising the topic and designing the framework to collecting and analysing the field data. B completed the manuscript writing. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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