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Allelopathic influence of fly ash and nitrogen on growth, yield attributes and productivity of mustard (*Brassica juncea* L.)

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Abstract

Fly ash, a coal combustion by-product enriched with calcium oxide, magnesium oxide, silicon dioxide, iron and manganese oxides, exerts bioactive influence on soil physico-chemical properties analogous to natural allelochemicals. Its combined application with nitrogen in mustard cultivation has been inadequately studied under the semi-arid conditions of Punjab. A field experiment was conducted during the rabi season of 2024–25 at the Agricultural Research Farm, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India. The experiment was laid out in a Split Plot Design with three fly ash levels (0, 5 and 10 t/ha) as main plots and four nitrogen levels (0, 37.5, 62.5 and 87.5 kg/ha) as sub-plots, replicated thrice, giving 12 treatment combinations. Mustard variety GSC-7 was sown on 03 October 2024. Growth parameters (plant height, primary and secondary branches per plant), yield attributes (siliqueae per plant, silique length, grains per silique and 1000-grain weight) and economic returns were recorded. Data were analysed using analysis of variance appropriate for Split Plot Design and means were compared at the 5% level of probability. Application of fly ash at 10 t/ha significantly enhanced plant height (137.47 cm), primary branches (6.22), secondary branches (10.81), siliqueae per plant (1357.83), silique length (5.34 cm), grains per silique (21.50), stover yield (22.73 q/ha) and seed yield (10.85 q/ha). Among nitrogen levels, 87.5 kg/ha recorded the highest seed yield (11.68 q/ha). The treatment combination of fly ash at 10 t/ha and nitrogen at 87.5 kg/ha recorded the maximum seed yield (12.68 q/ha), net return (₹49,160/ha) and benefit-to-cost ratio (2.21), and is recommended for mustard cultivation in the loamy-sand soils of Punjab.

Keywords: *Brassica juncea*, fly ash, mustard, nitrogen, seed yield, soil amendment

Introduction

Mustard (*Brassica juncea* L.) belonging to family Cruciferae is one of the most important rabi oilseed crops of northern India, contributing nearly 30% of total oilseed production and ranking second after groundnut (FAI, 2018) ^[4]. India leads globally in area under mustard and holds second position in production after China. In Punjab, mustard is cultivated on approximately 0.82 lakh hectares with a productivity of 926 kg/ha, considerably below the national average of 1581 kg/ha (FAI, 2018) ^[4], highlighting the need for improved agronomic practices. Edible oils from mustard are concentrated sources of essential fatty acids and fat-soluble vitamins, but current domestic oilseed production meets only about 50% of national demand (Khobragade *et al.*, 2008) ^[7].

Nitrogen is the most critical macronutrient for mustard, constituting protoplasm, chlorophyll and metabolically active proteins (Reddy and Reddy, 1998) ^[17]. *Brassica* species remove large quantities of nitrogen until flowering, and yield responses to nitrogen up to 87.5 kg/ha have been well documented (Malav *et al.*, 2024; Singh *et al.*, 2022; Sharma *et al.*, 2022) ^[11, 22, 20]. Fly ash (FA), the residue from coal combustion in thermal power plants, is generated in excess of 100 million tonnes annually in India (Mathur *et al.*, 2003) ^[12]. Its enrichment with calcium oxide, magnesium oxide, silicon dioxide and trace micronutrients enables FA to modify soil pH, bulk density, moisture retention and nutrient availability effects ecologically analogous to those of soil-applied allelochemicals (Adriano and Weber, 2001; Kuchanwar and Matte, 1997) ^[1, 8]. Recent studies have demonstrated significant yield improvements in *Brassica* crops from FA application (Singh *et al.*, 2020; Jana *et al.*, 2017; Sasmita Dash *et al.*, 2017) ^[21, 5, 19]. However,

the combined agronomic and biochemical effect of FA and nitrogen on mustard var. GSC-7 under Punjab's semi-arid conditions remains unquantified. The present investigation was undertaken to evaluate the effect of fly ash and nitrogen levels on growth and seed yield of mustard; and assess economic returns of different treatment combinations.

Materials and Methods

Experimental site and climate

The experiment was conducted during the rabi season (October

2024 – March 2025) at the Agricultural Research Farm, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India (29°57'N; 75°07'E; 213 m asl). The region has a sub-tropical, semi-arid climate with maximum summer temperature of 45°C and minimum winter temperature of 0.5°C. Mean annual rainfall is approximately 650 mm, of which three-fourths arrives during the south-west monsoon (July–September). Weekly meteorological data recorded during the crop season are presented in Table 1.

Table 1: Weekly mean meteorological data during rabi 2024–25 at Talwandi Sabo, Bathinda (selected weeks)

SMW	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	RH Morning (%)	RH Evening (%)	Rainfall (mm)	Evap. (mm)
41	28.3	12.4	20.4	95	38	0.0	8.1
43	24.6	9.8	17.2	97	46	0.0	4.6
45	20.9	6.0	13.5	99	49	0.0	7.6
47	20.1	3.1	11.6	99	46	0.0	6.5
49	16.6	3.0	9.8	99	56	2.0	8.0
50	14.3	7.7	11.0	94	83	38.0	2.0
2	21.7	6.1	13.9	96	45	0.0	6.3
5	20.9	8.1	14.5	89	52	0.0	6.5
8	26.4	10.8	18.6	89	39	0.0	8.8
11	35.1	18.6	26.9	76	31	0.0	9.3

Soil characteristics

Composite soil samples from 0–15 and 15–30 cm depths were analysed for physico-chemical properties prior to sowing (Table 2). The soil was loamy sand in texture, slightly alkaline (pH 7.6–8.0), low in organic carbon (0.12–0.24%) and available nitrogen (103–206 kg/ha), adequate in available phosphorus (26.2 kg/ha) and potassium (150–217 kg/ha).

Table 2: Physico-chemical properties of the experimental soil

Soil property	0–15 cm	15–30 cm	Method
Textural class	Loamy sand	Loamy sand	Pipette method
pH (1:2 soil:water)	7.6	8.0	Glass electrode
EC (dS/m)	0.15	0.10	Conductivity meter
Organic carbon (%)	0.24	0.12	Walkley–Black
Available N (kg/ha)	206	103	Alkaline KMnO ₄
Available P (kg/ha)	26.2	26.2	Olsen method
Available K (kg/ha)	150	217	Flame photometer

Treatments and experimental design

The experiment was laid out in a Split Plot Design (SPD) with three replications. Main plots comprised three fly ash levels: F₀ = 0 t/ha, F₁ = 5 t/ha and F₂ = 10 t/ha. Sub-plots comprised four nitrogen levels: N₀ = 0 kg/ha, N₁ = 37.5 kg/ha, N₂ = 62.5 kg/ha and N₃ = 87.5 kg/ha, giving 12 treatment combinations. Net plot size was 3.0 × 3.0 m. Variety GSC-7 was used throughout.

Crop management

Field preparation comprised two disc harrow passes followed by planking after pre-sowing irrigation. Fly ash was incorporated as per treatments before the last planking. A basal dose of 30 kg P₂O₅/ha (single super phosphate) and 15 kg K₂O/ha (muriate of potash) was applied uniformly. Fifty percent of allocated nitrogen (as urea, 46% N) was applied basally; the remaining 50% was top-dressed after the first irrigation. Variety GSC-7 was sown on 03 October 2024 at 3.75 kg/ha seed rate with 30 cm row spacing. Thinning at 22 days after sowing (DAS) maintained 15 cm plant-to-plant spacing. Three irrigations were given at 35, 75 and 95 DAS. Crop protection included Thiamethoxam 25 WG (100 g/ha) against aphids and Mancozeb 75 WP (625 g/ha) against *Alternaria* blight.

Observations and statistical analysis

Plant height (cm), primary and secondary branches per plant were recorded at maturity. Leaf area index was measured at 90 DAS using a Sun Scan Canopy Analyser. Yield attributes siliquae per plant, siliqua length (cm), grains per siliqua and 1000-grain weight (g) were recorded at harvest. Stover yield (q/ha) and seed yield (q/ha) were recorded after threshing and cleaning. Economic analysis used prevailing market prices. Data were subjected to ANOVA for SPD and treatment means compared using the Critical Difference (CD) at P=0.05.

Results and Discussion

Plant height (cm)

Plant height increased significantly with nitrogen and fly ash levels (Table 3). N₃ (87.5 kg/ha) gave the highest mean plant height (141.83 cm) and F₂ (10 t/ha) gave the tallest mean (137.47 cm). The interaction F₂N₃ recorded maximum plant height (143.44 cm) versus minimum in F₀N₀ (123.13 cm). Enhanced height with nitrogen is attributed to increased cell division, elongation and photosynthate production (Joshi *et al.*, 1991) [6], while FA through its alkaline chemistry and micronutrient supply created a growth-stimulatory rhizosphere environment (Sarita Gautam *et al.*, 2013) [18]. Similar findings were reported by Ansari *et al.* (2022) [2] and Kumar *et al.* (2021) [10].

Table 3: Effect of fly ash and nitrogen levels on plant height (cm) at maturity of mustard (*Brassica juncea* L.). FA = fly ash; CD = critical difference at P=0.05; NS = non-significant

Nitrogen level	F ₀ (0 t/ha)	F ₁ (5 t/ha)	F ₂ (10 t/ha)	Mean
N ₀ (0 kg/ha)	123.13	126.07	128.38	125.86
N ₁ (37.5 kg/ha)	131.07	134.22	136.52	133.94
N ₂ (62.5 kg/ha)	135.63	138.75	141.53	138.64
N ₃ (87.5 kg/ha)	140.35	141.68	143.44	141.83
Mean	132.55	135.18	137.47	–
CD (5%)	N: 1.31	FA: 0.66	N×FA: 2.61	–

Primary and secondary branches per plant

Primary branches per plant increased significantly with both

factors (Table 4). N₃ gave the highest mean (6.63) and F₂ recorded the highest fly ash mean (6.22), with F₂N₃ giving the maximum interaction value (6.86). Similarly, secondary branches were highest under N₃ (11.42) and F₂ (10.81), with F₂N₃ giving 11.85 and F₀N₀ the minimum (8.91) (Table 5). Increased branching with nitrogen reflects improved auxin and cytokinin synthesis promoting axillary bud development (Kumar and Kumar, 2008) [9]. FA-stimulated branching is consistent with Kuchanwar and Matte (1997) [8] and Sasmita Dash *et al.* (2017) [19] who documented similar responses in *Brassica* crops.

Table 4: Effect of fly ash and nitrogen levels on primary branches per plant at maturity of mustard (*Brassica juncea* L.).

Nitrogen level	F ₀ (0 t/ha)	F ₁ (5 t/ha)	F ₂ (10 t/ha)	Mean
N ₀ (0 kg/ha)	4.61	5.22	5.44	5.09
N ₁ (37.5 kg/ha)	5.59	5.89	6.07	5.85
N ₂ (62.5 kg/ha)	6.17	6.27	6.49	6.31
N ₃ (87.5 kg/ha)	6.42	6.61	6.86	6.63
Mean	5.70	5.99	6.22	—
CD (5%)	N: 0.15	FA: 0.08	N×FA: 0.29	—

Table 5: Effect of fly ash and nitrogen levels on secondary branches per plant at maturity of mustard (*Brassica juncea* L.).

Nitrogen level	F ₀ (0 t/ha)	F ₁ (5 t/ha)	F ₂ (10 t/ha)	Mean
N ₀ (0 kg/ha)	8.91	9.50	9.87	9.43
N ₁ (37.5 kg/ha)	9.43	9.78	10.23	9.81
N ₂ (62.5 kg/ha)	10.33	10.89	11.30	10.84
N ₃ (87.5 kg/ha)	11.00	11.41	11.85	11.42
Mean	9.92	10.40	10.81	—
CD (5%)	N: 0.19	FA: 0.11	N×FA: 0.41	—

Siliquae per plant and siliqua length

Siliquae per plant differed significantly due to both factors and their interaction (Table 6). F₂ gave the highest fly ash mean (1357.83) and N₃ gave the highest nitrogen mean (1422.44). The interaction F₂N₂ recorded the maximum (1500.67) and F₀N₀ the minimum (921.67). Nitrogen promotes cytokinin synthesis stimulating siliqua set, while FA improved soil structure and photosynthate supply to reproductive sinks, aligning with Ram *et al.* (2013) [13] and Singh *et al.* (2020) [21]. Siliqua length increased with both treatments (Table 7), with F₂ recording 5.34 cm and N₃ giving the highest mean (5.61 cm). Longer siliquae with higher nitrogen indicate improved assimilate supply to developing pods (Reager *et al.*, 2006) [16].

Table 6: Effect of fly ash and nitrogen levels on siliquae per plant at maturity of mustard (*Brassica juncea* L.).

Nitrogen level	F ₀ (0 t/ha)	F ₁ (5 t/ha)	F ₂ (10 t/ha)	Mean
N ₀ (0 kg/ha)	921.67	1055.33	1151.33	1042.78
N ₁ (37.5 kg/ha)	1269.33	1281.00	1332.00	1294.11
N ₂ (62.5 kg/ha)	1333.00	1383.67	1500.67	1405.78
N ₃ (87.5 kg/ha)	1396.67	1423.33	1447.33	1422.44
Mean	1230.17	1285.83	1357.83	—
CD (5%)	N: 30.05	FA: 30.56	N×FA: 61.12	—

Table 7: Effect of fly ash and nitrogen levels on siliqua length (cm) at maturity of mustard (*Brassica juncea* L.).

Nitrogen level	F ₀ (0 t/ha)	F ₁ (5 t/ha)	F ₂ (10 t/ha)	Mean
N ₀ (0 kg/ha)	5.00	4.76	5.04	4.93
N ₁ (37.5 kg/ha)	5.14	5.27	5.29	5.23
N ₂ (62.5 kg/ha)	5.40	5.41	5.48	5.43
N ₃ (87.5 kg/ha)	5.25	5.64	5.55	5.61
Mean	5.20	5.27	5.34	—
CD (5%)	N: 0.15	FA: 0.08	N×FA: 0.17	—

Grains per siliqua and 1000-grain weight

Grains per siliqua responded significantly to all treatments (Table 8). F₂ gave the highest mean (21.50) and N₃ gave the highest nitrogen mean (22.56), with F₂N₂ recording the maximum (24.00). Test weight was significantly influenced only by nitrogen levels; the fly ash effect and interaction were non-significant (Table 9). N₃ gave the highest test weight (4.51 g). Improved seed set with FA corroborates Swamy *et al.* (2010) [23], while the nitrogen response aligns with Malav *et al.* (2024) [11] and Sharma *et al.* (2022) [20].

Table 8: Effect of fly ash and nitrogen levels on grains per siliqua at maturity of mustard (*Brassica juncea* L.).

Nitrogen level	F ₀ (0 t/ha)	F ₁ (5 t/ha)	F ₂ (10 t/ha)	Mean
N ₀ (0 kg/ha)	13.33	16.33	18.67	16.11
N ₁ (37.5 kg/ha)	18.33	16.33	20.00	18.22
N ₂ (62.5 kg/ha)	19.00	18.00	24.00	20.33
N ₃ (87.5 kg/ha)	22.00	22.33	23.33	22.56
Mean	18.17	18.25	21.50	—
CD (5%)	N: 1.45	FA: 0.82	N×FA: 1.65	—

Table 9: Effect of fly ash and nitrogen levels on 1000-grain weight (g) of mustard (*Brassica juncea* L.). NS = non-significant

Nitrogen level	F ₀ (0 t/ha)	F ₁ (5 t/ha)	F ₂ (10 t/ha)	Mean
N ₀ (0 kg/ha)	4.24	4.27	4.37	4.29
N ₁ (37.5 kg/ha)	4.26	4.43	4.52	4.40
N ₂ (62.5 kg/ha)	4.28	4.43	4.56	4.42
N ₃ (87.5 kg/ha)	4.49	4.49	4.55	4.51
Mean	4.32	4.41	4.50	—
CD (5%)	N: 0.11	FA: NS	N×FA: NS	—

Stover yield and seed yield

Stover yield increased significantly with both treatments (Table 10). F₂ gave the highest mean (22.73 q/ha) and N₃ gave the highest nitrogen mean (25.19 q/ha), with F₂N₃ recording the maximum (25.81 q/ha) versus F₀N₀ minimum (14.93 q/ha). Seed yield showed a significant response to all factors (Table 11). F₂ gave the highest fly ash mean (10.85 q/ha) compared to F₀ (9.83 q/ha). N₃ gave the highest nitrogen mean (11.68 q/ha), statistically at par with N₂ (11.35 q/ha). The maximum seed yield (12.68 q/ha) was recorded in F₂N₃ and the minimum (7.36 q/ha) in F₀N₀. Higher seed yield with nitrogen is attributable to better branching, siliqua number and grain filling, while FA-mediated improvements in soil conditions enhanced nitrogen-use efficiency (Singh *et al.*, 2020; Jana *et al.*, 2017; Rautaray *et al.*, 2003) [21, 5, 15].

Table 10: Effect of fly ash and nitrogen levels on stover yield (q/ha) of mustard (*Brassica juncea* L.).

Nitrogen level	F ₀ (0 t/ha)	F ₁ (5 t/ha)	F ₂ (10 t/ha)	Mean
N ₀ (0 kg/ha)	14.93	16.72	17.64	16.43
N ₁ (37.5 kg/ha)	19.68	21.69	22.34	21.23
N ₂ (62.5 kg/ha)	22.95	24.15	25.16	24.30
N ₃ (87.5 kg/ha)	25.54	24.92	25.81	25.19
Mean	20.77	21.87	22.73	—
CD (5%)	N: 0.55	FA: 0.34	N×FA: 0.68	—

Table 11: Effect of fly ash and nitrogen levels on seed yield (q/ha) of mustard (*Brassica juncea* L.).

Nitrogen level	F ₀ (0 t/ha)	F ₁ (5 t/ha)	F ₂ (10 t/ha)	Mean
N ₀ (0 kg/ha)	7.36	8.64	9.18	8.39
N ₁ (37.5 kg/ha)	9.58	9.90	10.31	9.93
N ₂ (62.5 kg/ha)	11.44	11.39	11.22	11.35
N ₃ (87.5 kg/ha)	10.94	11.42	12.68	11.68
Mean	9.83	10.34	10.85	—
CD (5%)	N: 0.58	FA: 0.20	N×FA: 0.41	—

Economic analysis

The benefit-to-cost (B:C) ratio improved with increasing levels of both inputs (Table 12). The highest cost of cultivation (₹40,600/ha) was recorded under F₂N₃, yet this treatment also gave the maximum gross return (₹89,760/ha), net return (₹49,160/ha) and B:C ratio (2.21) rising from 1.43 under F₀N₀. These results are consistent with Malav *et al.* (2024) ^[11] and Singh *et al.* (2022) ^[22], confirming the economic advantage of combining fly ash with optimised nitrogen in *Brassica* cultivation.

Table 12: Effect of fly ash and nitrogen levels on economics of mustard (*Brassica juncea* L.) cultivation

Treatment	Cost of cultivation (₹/ha)	Gross return (₹/ha)	Net return (₹/ha)	B:C ratio
N ₀ F ₀	36,000	51,520	15,520	1.43
N ₁ F ₀	37,800	66,060	28,260	1.75
N ₂ F ₀	39,000	79,960	40,960	2.05
N ₃ F ₀	40,200	76,580	36,380	1.90
N ₀ F ₁	36,200	60,480	24,280	1.67
N ₁ F ₁	38,000	68,460	30,460	1.80
N ₂ F ₁	39,200	79,730	40,530	2.03
N ₃ F ₁	40,400	80,940	40,540	2.00
N ₀ F ₂	36,400	64,260	27,860	1.76
N ₁ F ₂	38,200	71,330	33,130	1.86
N ₂ F ₂	39,400	78,540	39,140	2.00
N ₃ F ₂	40,600	89,760	49,160	2.21

Conclusion

Fly ash at 10 t/ha acts as a bioactive soil amendment with growth-stimulatory biochemical effects on mustard (*Brassica juncea* L.) analogous to allelopathic enhancement, by modifying the soil chemical environment and improving nutrient availability. Combined application of fly ash at 10 t/ha and nitrogen at 87.5 kg/ha (F₂N₃) recorded the highest seed yield (12.68 q/ha), net return (₹49,160/ha) and B:C ratio (2.21), and is recommended for mustard cultivation in the loamy-sand soils of semi-arid Punjab. Fly ash utilisation as a soil amendment provides an environmentally responsible approach to managing industrial coal combustion residue while enhancing crop productivity. Future research should examine the long-term soil health implications of repeated fly ash application and validate these findings over multiple seasons.

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