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Issue Article

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EFFECT OF BENTONITE APPLICATION METHOD, TIMING AND RATE ON FIELD EMERGENCE, GROWTH, NODULATION AND YIELD STRUCTURE OF SOYBEAN

Abstract: *The effects of the method, timing and rate (100–750 kg ha^{-1}) of bentonite application against an $N_{90}P_{60}K_{90}$ background on field emergence, plant density, growth, nodulation and yield structure of soybean cv. 'Uzbek-6' were studied on light serozem soils of Kashkadarya region (2024–2026). Bentonite applied at sowing increased field emergence from 84.1 % to 84.8–87.2 % and final plant density by 1.5–6.8 %, whereas split application at budding and flowering increased seed mass per plant by 3.6–13.8 %. Plant density correlated closely with bentonite rate (r = 0.925–0.991) and field emergence (r = 0.924), and seed mass per plant with plant survival (r = 0.903).*

Key words: *soybean, bentonite, light serozem, field emergence, plant density, leaf area index, nodulation, yield structure, correlation, regression.*

Language: *English*

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Introduction

Soybean (*Glycine max* (L.) Merr.) is a protein and oil-rich legume capable of biological nitrogen fixation. The light serozem soils of Kashkadarya region are low in humus and retain little water, so uniform emergence and an optimal plant stand are key yield factors there. Soybean emergence declines sharply with the number of days of insufficient seed-zone moisture (T.C.Helms *et al*., 1996) and with increasing soil crust strength (R.J.Hanks va Thorp F.C.; 1957).

Natural mineral amendments such as bentonite, zeolite and glauconite are increasingly used to improve soils (F.A.Mumpton, 1999). In semi-arid China, 6-30 t ha^{-1} of bentonite increased field water-holding capacity, millet emergence and photosynthesis (J.Mi, *et al*., 1996) and soil microbial biomass by 3-50 % (J.Mi, *et al*., 2021). In a long-term Polish experiment, bentonite increased organic carbon, total nitrogen (J.Czaban *et al*., 2013), cation exchange capacity and available P and K in sandy soil (J.Czaban and Siebielec G., 2013); similar effects were found in tropical sandy soil (J.Croker *et al*., 2004), and a bentonite-humic acid amendment remained effective for 4-5 years (L.Zhou *et al*., 2022, B.Ma *et al*., 2022).

Soybean productivity depends on nodule bacteria, whose activity is inhibited by soil mineral nitrogen, especially nitrate (J.G.Streeter, 1988, N.Yamashita, 2019). Locally, bentonite seed coating has been studied for winter wheat on light serozem soils (X.R.Tog'ayeva, 2026), but the effects of the method, timing and low rates (100–750 kg ha^{-1}) of bentonite application on soybean have not been sufficiently studied.

The aim of the study was to determine the effect of bentonite application method, timing and rate on field emergence, plant density, growth, nodulation and yield structure of soybean and to assess the correlation and regression relationships between these traits.

MATERIALS AND METHODS

Field experiments were conducted in 2024-2026 at the central experimental site of the Southern Research Institute of Agriculture (Karshi district, Kashkadarya region) on light serozem soils in a 1:1 (legume: cereal) short-rotation system. Variety of soybean "Uzbek-6", included in the State Register, was sown as a main crop at 60×5 cm (theoretical density 333.3 thousand plants ha^{-1}); seeds were treated with nitragin before sowing.

The experiment comprised 14 treatments (Table 1) in three replications arranged in a single tier. Plots were 4.8 m wide (furrow spacing 60 cm) and 50 m long (240 m^2), with a recorded area of 120 m^2; the total experimental area was 1.0 ha.

Mineral fertilizers (ammonium nitrate, 34 % N; superphosphate, 20 % P_2O_5; potassium salt, 40 % K_2O) were applied at $N_{90}P_{60}K_{90}$ kg ha^{-1} in all treatments except treatment 8: phosphorus and potassium entirely before ploughing, and nitrogen in two equal doses at the beginning of budding and at flowering (75-80 % of plants flowering).

Bentonite clay was applied at 100, 200, 300, 400, 500 and 750 kg ha^{-1} together with mineral fertilizers using a cultivator: at sowing (treatments 9-14), in equal parts at budding and flowering (treatments 3-7), or at sowing, budding and flowering at 250 kg ha^{-1} each (treatment 2). Treatment 1 ($N_{90}P_{60}K_{90}$) and treatment 8 (no mineral fertilizers; 750 kg ha^{-1} bentonite before autumn ploughing) served as controls.

Field emergence and final plant density were determined by plant counts, and survival as the ratio of final to emerged plants (B.A.Dospekhov, 1985). In 2024, plant height, leaf area (disc method; LAI calculated from leaf area per plant and plant density), nodule number and mass (A.A.Nichiporovich, 1963) and yield structure were determined. Correlation and regression analyses were performed on treatment means in Python 3 (SciPy); model significance was assessed by F- and t-tests ($p < 0.05$), and application methods were compared using a paired t-test.

RESULTS AND DISCUSSION

In the control ($N_{90}P_{60}K_{90}$), field emergence was 84.1 % and the number of emerged plants was 280.2 thousand ha^{-1} (Table 1). Bentonite applied at sowing increased field emergence from 84.8 % (100 kg ha^{-1}) to 87.2 % (750 kg ha^{-1}), and the number of emerged plants exceeded the control by 2.6-10.3 thousand ha^{-1}.

When bentonite was applied at budding and flowering (treatments 3-7), emergence (83.8-84.4 %) did not differ from the control, since bentonite was applied after emergence ($r = 0.293$; $p = 0.573$).

Table 1. Effect of bentonite application method, timing and rate on field emergence and plant density of soybean (mean of 2024–2026)

No.	Treatment (bentonite rate, kg ha^{-1})	Bentonite application timing, kg ha^{-1}			Field emergence, %	Emerged plants, thousand ha^{-1}	Final plant density, thousand ha^{-1}	Plant survival, %
		at sowing	budding	flowering				
1	Control ($N_{90}P_{60}K_{90}$)	–	–	–	84.1	280.2	245.9	87.8
2	$N_{90}P_{60}K_{90}$ + 750	250	250	250	85.6	285.3	257.1	90.1
3	$N_{90}P_{60}K_{90}$ + 100	–	50	50	84.2	280.8	248.3	88.4
4	$N_{90}P_{60}K_{90}$ + 200	–	100	100	83.8	279.2	248.9	89.1
5	$N_{90}P_{60}K_{90}$ + 300	–	150	150	83.9	279.7	251.0	89.7
6	$N_{90}P_{60}K_{90}$ + 400	–	200	200	84.4	281.3	252.4	89.7
7	$N_{90}P_{60}K_{90}$ + 500	–	250	250	84.2	280.5	253.5	90.4
8	Control (750 kg ha^{-1} before autumn ploughing)	–	–	–	84.9	283.1	249.3	88.1
9	$N_{90}P_{60}K_{90}$ + 750	750	–	–	87.2	290.5	262.6	90.4
10	$N_{90}P_{60}K_{90}$ + 100	100	–	–	84.8	282.8	249.7	88.3
11	$N_{90}P_{60}K_{90}$ + 200	200	–	–	85.5	284.8	253.4	89.0
12	$N_{90}P_{60}K_{90}$ + 300	300	–	–	86.3	287.8	258.0	89.7
13	$N_{90}P_{60}K_{90}$ + 400	400	–	–	87.0	290.1	260.8	89.9
14	$N_{90}P_{60}K_{90}$ + 500	500	–	–	86.9	289.5	260.3	89.9

Note: seeds were sown as a main crop at 60 × 5 cm (theoretical density 333.3 thousand plants ha^{-1}).

Plant density and survival

In the control, final plant density was 245.9 thousand ha^{-1} and plant survival 87.8 %. Bentonite applied at sowing increased final density to 249.7–262.6 thousand ha^{-1}, i.e. by 3.8–16.7 thousand ha^{-1} (1.5–6.8 %); the difference between 750 and 400 kg ha^{-1} was only 1.8 thousand ha^{-1} (0.7 %).

When bentonite was applied at budding and flowering, emergence did not change, but survival increased from 88.4 % (100 kg ha^{-1}) to 90.4 % (500 kg ha^{-1}), and final density exceeded the control by 2.4–7.6 thousand ha^{-1} (1.0–3.1 %). At equal rates (100–500 kg ha^{-1}), application at sowing provided 1.4–8.4 thousand ha^{-1} more plants than split application ($p = 0.010$), mainly due to better emergence ($p = 0.007$).

Table 2. Effect of bentonite application method, timing and rate on plant height, leaf area index and nodule number of soybean (2024)

No.	Treatment (bentonite rate, kg ha^{-1})	Plant height, cm				Leaf area index, m^2 m^{-2}					Nodules, no. plant^{-1}		
		B	F	PG	M	TL	B	F	PF	PR	B	F	PG
Control treatments													
1	Control ($N_{90}P_{60}K_{90}$)	34.3	61.3	87.8	94.1	0.23	1.15	3.04	3.85	2.08	13.9	26.7	20.2
8	Control (750 kg ha^{-1} before autumn ploughing)	30.3	55.1	78.9	84.6	0.23	0.98	2.66	3.24	1.53	20.2	35.9	28.2
Bentonite at sowing													
10	$N_{90}P_{60}K_{90}$ + 100	35.1	62.0	90.9	97.8	0.24	1.17	3.18	3.87	2.17	15.3	27.5	23.3
11	$N_{90}P_{60}K_{90}$ + 200	35.6	62.7	92.1	97.8	0.25	1.22	3.23	4.03	2.26	16.2	29.1	23.5
12	$N_{90}P_{60}K_{90}$ + 300	35.6	62.7	91.2	96.7	0.26	1.23	3.21	4.12	2.29	17.0	29.4	24.0
13	$N_{90}P_{60}K_{90}$ + 400	35.8	63.5	91.6	97.5	0.25	1.26	3.34	4.13	2.27	17.6	29.3	24.8
14	$N_{90}P_{60}K_{90}$ + 500	35.9	63.1	92.5	98.9	0.25	1.26	3.35	4.17	2.37	17.5	29.6	24.9
9	$N_{90}P_{60}K_{90}$ + 750	36.4	63.7	92.2	99.6	0.25	1.27	3.33	4.28	2.39	17.4	31.2	24.1
Bentonite at budding and flowering (50 : 50)													
3	$N_{90}P_{60}K_{90}$ + 100	33.8	61.4	89.8	96.9	0.25	1.13	3.10	4.10	2.21	14.1	26.8	22.3
4	$N_{90}P_{60}K_{90}$ + 200	33.9	61.7	91.7	97.5	0.24	1.16	3.20	4.17	2.28	14.3	27.7	24.1
5	$N_{90}P_{60}K_{90}$ + 300	34.3	62.4	92.6	100.3	0.24	1.14	3.18	4.27	2.40	13.4	28.0	23.6
6	$N_{90}P_{60}K_{90}$ + 400	33.9	61.4	93.3	99.4	0.24	1.16	3.19	4.31	2.42	14.2	27.5	24.4
7	$N_{90}P_{60}K_{90}$ + 500	34.2	61.4	93.8	101.3	0.24	1.14	3.16	4.36	2.46	14.3	28.5	24.4
Bentonite at sowing, budding and flowering (250 + 250 + 250 kg ha^{−1})													
2	$N_{90}P_{60}K_{90}$ + 750	35.8	64.8	94.2	101.5	0.25	1.20	3.39	4.41	2.45	16.6	31.6	27.0

Note: TL – trifoliate leaf, B – budding, F – flowering, PF – pod formation, PG – pod filling, PR – pod ripening, M – maturity; seeds were treated with nitragin; nodules were counted by the monolith method on five plants from replications 1 and 3.

Plant height and leaf area index

Bentonite applied at sowing accelerated growth from the early stages: plant height was 35.1–36.4 cm at budding (control 34.3 cm; +2.3–6.1 %) and 96.7–99.6 cm at maturity (control 94.1 cm; +2.8–5.8 %) (Table 2). Split application did not affect height up to flowering, but accelerated later growth: at maturity plants reached 96.9–101.3 cm (+3.0–7.7 %). The tallest plants were recorded in treatment 2 (101.5 cm) and the shortest in treatment 8 without mineral fertilizers (84.6 cm; 10.1 % below the control).

LAI peaked at pod formation (control 3.85 m^2 m^{-2}). Bentonite applied at sowing increased LAI at budding by 1.7–10.4 % and at flowering by 4.6–10.2 %. Split application did not change LAI in the early stages, but at pod formation it reached 4.10–4.36 m^2 m^{-2} (+6.5–13.2 %), significantly exceeding application at sowing ($p < 0.001$); leaf area per plant was also the largest in these treatments (1651–1720 cm^2). The highest LAI was found in treatment 2 (4.41) and the lowest in treatment 8 (3.24; 15.8 % below the control).

Nodulation

Nodulation peaked at flowering (Table 2). Bentonite applied at sowing enhanced nodulation already at budding: nodule number increased to 15.3–17.6 per plant (control 13.9; +10.1–26.6 %) and nodule fresh mass to 0.42–0.52 g per plant (+13.5–40.5 %). Split application increased nodule number only at pod filling (22.3–24.4 per plant; +10.4–20.8 %), whereas at budding ($p = 0.005$) and flowering ($p = 0.002$) application at sowing was superior. Most nodules were formed in treatment 8 without mineral fertilizers (+34.5–45.3 %), although its plants were the shortest, owing to the absence of nitrogen inhibition. Among $N_{90}P_{60}K_{90}$ treatments, the best nodulation was observed in treatment 2 (31.6 nodules and 1.25 g per plant at flowering).

Yield structure

Bentonite improved all yield components (Table 3). In the control, a plant had 2.1 branches, 38.0 pods and 87.4 seeds with a seed mass of 13.76 g, and the 1000-seed weight was 157.4 g. Application at sowing increased seed mass per plant to 14.01–15.29 g (+1.8–11.1 %), mainly at 400–750 kg ha^{-1}. Split application at budding and flowering was more effective: plants had 38.4–39.8 pods and 88.3–95.5 seeds, seed mass reached 14.25–15.66 g per plant (+3.6–13.8 %) and the 1000-seed weight 161.4–164.1 g. At equal rates, split application exceeded application at sowing in the number of branches ($p = 0.004$) and pods ($p = 0.001$) and in seed mass per plant ($p = 0.025$).

Among $N_{90}P_{60}K_{90}$ treatments, the highest seed mass per plant was obtained in treatments 7 (500 kg ha^{-1} split; 15.66 g) and 2 (15.62 g). Treatment 8 had the poorest yield structure (29.1 pods, 58.2 seeds and 8.24 g of seeds per plant; −40.1 %), indicating that abundant nodulation did not compensate for the absence of mineral fertilizers.

Correlation and regression analysis

With application at sowing, bentonite rate was closely related to field emergence ($r = 0.919$) and final plant density ($r = 0.925$) (Table 4). Quadratic models fitted better ($r^2 = 0.984$): the maximum plant density (262.6 thousand ha^{-1}) corresponds to about 680 kg ha^{-1}, while at 400 kg ha^{-1} density reaches 98.9 % of the maximum. Quadratic models for nodule number at budding ($r^2 = 0.992$) and seed mass per plant ($r^2 = 0.908$) reach their maxima at about 560 and 710 kg ha^{-1}, respectively.

With split application, bentonite rate was not related to emergence or early nodulation, but showed close linear relationships with final density ($r = 0.991$), LAI at pod formation ($r = 0.943$) and seed mass per plant ($r = 0.974$): each additional 100 kg ha^{-1} increased density by 1.5 thousand ha^{-1} and seed mass by 0.41 g per plant.

Table 3. Effect of bentonite application method, timing and rate on yield structure of soybean (2024)

No.	Treatment (bentonite rate, kg ha^{-1})	Height of first pod, cm	Per plant				1000-seed weight, g
			branches, no.	pods, no.	seeds, no.	seed mass, g	
Control treatments							
1	Control ($N_{90}P_{60}K_{90}$)	13.5	2.1	38.0	87.4	13.76	157.4
8	Control (750 kg ha^{-1} before autumn ploughing)	12.9	1.8	29.1	58.2	8.24	141.6
Bentonite at sowing							
10	$N_{90}P_{60}K_{90}$ + 100	13.7	2.2	38.2	87.9	14.01	159.5
11	$N_{90}P_{60}K_{90}$ + 200	14.1	2.2	38.3	88.1	14.24	161.7
12	$N_{90}P_{60}K_{90}$ + 300	14.3	2.3	38.8	89.2	14.50	162.5

13	$N_{90}P_{60}K_{90}$ + 400	14.3	2.2	39.2	94.1	15.29	162.5
14	$N_{90}P_{60}K_{90}$ + 500	14.4	2.3	39.4	94.6	15.25	161.3
9	$N_{90}P_{60}K_{90}$ + 750	14.1	2.3	39.0	93.6	15.22	162.6
Bentonite at budding and flowering (50 : 50)							
3	$N_{90}P_{60}K_{90}$ + 100	14.1	2.3	38.4	88.3	14.25	161.4
4	$N_{90}P_{60}K_{90}$ + 200	13.9	2.3	38.7	89.0	14.41	161.9
5	$N_{90}P_{60}K_{90}$ + 300	14.3	2.4	39.2	94.1	15.27	162.3
6	$N_{90}P_{60}K_{90}$ + 400	14.2	2.4	39.5	94.8	15.56	164.1
7	$N_{90}P_{60}K_{90}$ + 500	14.5	2.4	39.8	95.5	15.66	163.9
Bentonite at sowing, budding and flowering (250 + 250 + 250 kg ha^{−1})							
2	$N_{90}P_{60}K_{90}$ + 750	14.4	2.4	39.8	95.5	15.62	163.5

Note: the number of branches refers to first-order branches of the main stem.

Table 4. Regression equations of soybean traits on bentonite rate

Trait (y)	Method	Regression equation	r	R^2	p
Field emergence, %	At sowing	$y = 84.00 + 0.00976x - 7.32 \cdot 10^{-6}x^2$	0.919	0.984	< 0.001
	Split	not significant	0.293	0.086	0.573
Final plant density, thousand ha^{-1}	At sowing	$y = 245.53 + 0.0502x - 3.68 \cdot 10^{-5}x^2$	0.925	0.984	< 0.001
	Split	$y = 246.26 + 0.0150x$	0.991	0.983	< 0.001
Nodules at budding, no. $plant^{-1}$	At sowing	$y = 13.98 + 0.0136x - 1.21 \cdot 10^{-5}x^2$	0.840	0.992	< 0.001
	Split	not significant	0.217	0.047	0.679
LAI at pod formation, m^2 m^{-2}	At sowing	$y = 3.873 + 0.000594x$	0.958	0.918	0.001
	Split	$y = 3.942 + 0.000937x$	0.943	0.890	0.005
Seed mass per plant, g	At sowing	$y = 13.62 + 0.00473x - 3.31 \cdot 10^{-6}x^2$	0.899	0.908	0.009
	Split	$y = 13.80 + 0.00408x$	0.974	0.950	0.001

Note: x – bentonite rate, kg ha^{-1}; r – Pearson correlation coefficient; R^2 – coefficient of determination of the model; p – significance level of the model. At sowing n = 7 (0–750 kg ha^{-1}); split application (budding + flowering) n = 6 (0–500 kg ha^{-1}).

Table 5. Pairwise correlation coefficients between traits (n = 13)

Traits	1	2	3	4	5	6	7
1. Field emergence	1						
2. Final plant density	0.924**	1					
3. Plant survival	0.493	0.788**	1				
4. Nodule number (F)	0.756**	0.855**	0.735**	1			
5. Plant height (F)	0.745**	0.772**	0.550	0.923**	1		
6. LAI (F)	0.776**	0.863**	0.705**	0.886**	0.902**	1	
7. Seed mass per plant	0.274	0.594*	0.903**	0.546	0.428	0.603*	1

*Note: * – p < 0.05; ** – p < 0.01; F – flowering; treatment 8 was excluded because of its different fertilizer background.*

Across the 13 treatments with the same fertilizer background, final plant density was closely correlated with field emergence (r = 0.924), nodule number (r = 0.855), LAI (r = 0.863) and plant survival (r = 0.788) (Table 5); according to the coefficient of determination (d = 85.4 %), most of the variation in density is explained by emergence. Plant height and LAI at flowering were closely related to nodule number (r = 0.923 and 0.886); the LAI–density correlation is partly methodological. Seed mass per plant was closely related to plant survival (r = 0.903), LAI at pod formation (r = 0.905) and plant height at maturity (r = 0.849), but not to field emergence (r = 0.274).

Thus, bentonite at sowing mainly increases plant density through emergence, whereas later application improves individual plant productivity through survival and leaf area in the reproductive period. Unlike earlier studies, where bentonite was applied at several to tens of tonnes per hectare [5–9], 0.1–0.75 t ha^{-1} applied with mineral fertilizers was effective here.

CONCLUSIONS

1. On light serozem soils, bentonite applied at sowing at 100–750 kg ha^{-1} with $N_{90}P_{60}K_{90}$ increased soybean field emergence from 84.1 % to 84.8–87.2 %, final plant density by 1.5–6.8 %, nodule number at budding by 10.1–26.6 % and LAI at flowering by 4.6–10.2 %.

2. Split application at budding and flowering did not affect emergence or early growth, but increased plant survival up to 90.4 %, LAI at pod formation by 6.5–13.2 % and seed mass per plant by 3.6–13.8 %, exceeding application at sowing in yield structure.

3. Final plant density was closely related to bentonite rate (r = 0.925–0.991), field emergence (r = 0.924) and nodule number (r = 0.855), and seed mass per plant to plant survival (r = 0.903) and LAI at pod formation (r = 0.905).

4. Bentonite at 400 kg ha^{-1} applied at sowing provides 99.3 % of the plant density obtained at 750 kg ha^{-1} while reducing bentonite use by 46.7 %, whereas 400–500 kg ha^{-1} split between budding and flowering provides the best yield structure. The final choice of rate and timing should be based on grain yield and economic efficiency.

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