NARDI FUNDULEA, ROMANIA ROMANIAN AGRICULTURAL RESEARCH, NO. 43, 2026
www.incda-fundulea.ro; doi.org/10.59665/rar4375 First Online: July, 2026. DII 2067-5720 RAR 2026-188

Terracalco 95 (calcium oxide) Influence on Soybean Yield and Quality under Transylvanian Plain Conditions

Bogdan Costea[1], Felicia Chețan[2*], Cornel Chețan[2], Alina Șimon[2], Camelia Urdă[2], Laura Șopterean[2]

[1]University of Life Sciences "King Mihai I", 119 Calea Aradului, Timişoara, Timiş County, Romania
[2]Agricultural Research and Development Station Turda, 27 Agriculturii Street, 401100 Turda, Cluj County, Romania
[*]Corresponding author. E-mail: felicia.chetan@scdaturda.ro

ABSTRACT

Soybean yield is strongly influenced by soil chemical properties, particularly soil acidity, which affects nutrient availability, plant development, and biological processes such as symbiotic nitrogen fixation. The use of effective soil amendments represents an important strategy for improving soil fertility and maintaining crop productivity under sustainable agricultural systems. A three-year field experiment (2023-2025) conducted at the Agricultural Research and Development Station Turda (ARDS Turda), located in the Transylvanian Plain, evaluated the effects of *Terracalco 95,* a highly reactive calcium oxide-based soil amendment (CaO >95%; PNA = 175; Carmeuse Europe S.A.), on soybean yield, grain quality, nodulation, and plant height (Felix variety). Seven treatments included an untreated control and *Terracalco 95* applied at rates of 100 and 300 kg ha^{-1} before sowing, after sowing, and at the 3-5 trifoliate leaf stage, using a randomized complete block design with three replications and 48 m^2 plots. The soil showed near-neutral pH values in water (6.74-7.78) but relatively high hydrolytic acidity (Ah = 6.07-6.41 meq 100 g^{-1} in 2023), indicating substantial reserve acidity typical of clay-illuviated Phaeozems of the Transylvanian Plain. Following amendment application, hydrolytic acidity decreased markedly to 2.43-2.80 meq 100 g^{-1} by 2024-2025 (-55 to -60%), confirming effective neutralization of potential acidity. Combined ANOVA across years (error df = 12) revealed highly significant year effects ($p < 0.001$) for yield, hectoliter mass, 1000-seed mass, fat content, and nodulation traits. Treatment effects were not statistically significant for any measured parameter; however, all *Terracalco 95* treatments numerically exceeded the control, with mean yield increases ranging from 3.3% to 6.0% over the three-year period. The most consistent yield increases were observed for treatments V5 (+5.9%) and V7 (+6.0%), both corresponding to the 100 kg ha^{-1} rate. Nodule number and nodule weight showed the highest treatment F-values among all analyzed traits, suggesting a possible stimulatory effect on symbiotic nitrogen fixation.

Keywords: soybean, calcium amendment, hydrolytic acidity, nodulation, application timing.

INTRODUCTION

Soybean [*Glycine max* (L.) Merr.] is among the most economically important grain legumes worldwide (Șimon et al., 2025), valued for its high seed protein (35-45%) and oil content (18-22%), as well as its capacity for biological nitrogen fixation through symbiosis with *Bradyrhizobium japonicum* (Sprent et al., 2017; Singh et al., 2019; Urdă et al., 2026). In Romania, soybean cultivation has expanding in recent years, particulary in the Transylvanian Plain (Chețan et al., 2026), where clay-illuviated Phaeozems and vertic Chernozems provide high intrinsic fertility but frequently exhibit elevated hydrolytic acidity (Ah), despite near-neutral pH values in water. This dissociation between active and potential acidity is central to understanding the agronomic response to calcium amendments in this region (Dumitru et al., 2011; Lăcătușu et al., 2016).

Hydrolytic acidity reflects the reserve pool of H^+ and Al^{3+} ions bound to the soil colloidal complex,primarily on clay mineral and humic substance- that are not immediately expressed in the soil solution but can be mobilized under root acidification, intensive nitrogen fertilization, or microbial activity. Elevated Ah impairs aggregate stability, reduces calcium saturation of exchange sites, and negatively affects rhizobia activity and root nodule formation. For soybean, this is particularly significant because *Bradyrhizobium japonicum* activity and nodulation efficiency are sensitive to soil pH and calcium

Received 14 May 2026; accepted 17 July 2026.

availability; suboptimal Ca^{2+} supply reduces nodule initiation, infection thread formation, and nitrogen fixation rates (Haynes and Naidu, 1998; White and Broadley, 2003).

Reactive calcium oxide (CaO) amendments rapidly neutralize both active and reserve acidity, saturate exchange sites with Ca^{2+}, and promote clay flocculation and aggregate stability. These effects improve soil macroporosity, root penetration, and the chemical environment for rhizobia activity-benefits that are expected to translate into improved nodulation, plant development, and ultimately yield in soybean (White and Broadley, 2003; Brady and Weil, 2008).

Terracalco 95 (Carmeuse Europe S.A.; CaO >95%; PNA = 175) is a highly reactive granular quicklime whose effects on soybean performance under the specific pedoclimatic conditions of the Transylvanian Plain have not yet been documented.

The objectives of this study were: (i) to evaluate the effects of *Terracalco 95* applied at rate of 100 and 300 kg ha^{-1} at three timings on soybean yield, grain quality, nodulation, and plant height; (ii) to monitor soil hydrolytic acidity dynamics over three growing seasons; and (iii) to assess statistical significance using combined multi-year ANOVA and LSD analysis (Poly Fact, 2015).

MATERIAL AND METHODS

Experimental site and soil characterisation

The field experiment was conducted at Agricultural Research and Development Station (ARDS) Turda), situated in the south-western Transylvanian Plain (Barșon et al., 2021). Dominant soils are clay-illuviated Phaeozems and cambic to vertic Chernozems (RSTS, 2012) with medium-heavy clay texture and good hydrophobic properties (Chețan, 2019). Soil samples were collected annually before the establishment of the experiment and analyzed at the Office for Pedological and Agrochemical Studies (OPAS) Alba Iulia. Soil reaction (pH) was determined potentiometrically in a 1:2.5 soil-to-water suspension; hydrolytic acidity by Kappen method; humus by Walkley-Black; mineral nitrogen index by anaerobic incubation; available phosphorus and potassium using the Egner-Riehm method (Kabala and Jedrzejewski, 2024). The main soil chemical characteristics of the experimental field are presented in Table 1.

Table 1. Soil analytical data, ARDS Turda, 2023-2025

Year	Treatment	pH_{H_2O}	Ah (meq/100 g)	H%	IN	P (ppm)	K (ppm)
2023	V1control	6.76	6.41	4.92	4.82	51.2	257
	V2-3	6.81	6.19	5.34	5.23	39.5	221
	V4-5	7.78	6.23	5.46	5.35	23.5	242
	V6-7	6.74	6.07	5.22	5.12	40.9	234
2024	V1control	6.82	2.45	4.98	4.88	32.8	215
	V2-3	6.69	2.62	4.62	4.52	42.9	224
	V4-5	6.71	2.62	4.74	4.64	29.8	223
	V6-7	6.58	2.80	4.68	4.58	20.1	207
2025	V1control	6.79	2.43	4.98	4.81	32.7	220
	V2-3	6.81	2.54	4.71	4.60	41.4	222
	V4-5	6.89	2.51	4.76	4.71	30.7	219
	V6-7	6.67	2.72	4.49	4.62	21.4	217

Experimental design and treatments

Seven treatments (V1-V7) were arranged in a RCBD with three replications (48 m² per plot; 1,200 m² total). Soybean Felix variety was used in all three seasons. Treatments are described in Table 2.

Table 2. Experimental treatments, ARDS Turda, 2023-2025

Treatment	Description	Rate	Timing
V1 control	Control (no amendment)	–	–
V2	*Terracalco 95*, before sowing	300 kg ha^{-1}	April
V3	*Terracalco 95*, before sowing	100 kg ha^{-1}	April
V4	*Terracalco 95*, after sowing	300 kg ha^{-1}	April
V5	*Terracalco 95*, after sowing	100 kg ha^{-1}	April
V6	*Terracalco 95*, vegetation (3-5 leaf)	300 kg ha^{-1}	May-June
V7	*Terracalco 95*, vegetation (3-5 leaf)	100 kg ha^{-1}	May-June

Agronomic operations

Autumn ploughing was performed annually during the second decade of October, followed in spring by seedbed preparation with a rotary harrow one day before sowing. Soybean, cultivar Felix was sown an inter-row spacing of 18 cm using a Directa 400 seeder. At sowing, a basal fertilizer dose of $N_{40}P_{40}$ was applied simultaneously with seed placement. Pre-emergence weed control was carried out immediately after sowing using a mixture of Sencor Liquid at 0.35 L ha^{-1} and Spectrum at 1.2 L ha^{-1}. Post-emergence weed control, applied at the 2-4 trifoliate leaf stage, consisted of Corum at 1.9 L ha^{-1} for dicotyledonous weeds, followed 3 days later by Agil at 1.0 L ha^{-1} for monocotyledonous weeds. Harvesting was performed during the first decade of October of each year using Wintersteiger combine, with 16.8 m^2 harvested from each plot.

Nodulation assessment

Nodulation was assessed at the end of flowering stage (BBCH 67) according to the scale proposed by Feller et al. (1995) by excavating five plants per treatment together with the adhering soil. All nodules on the root systems of each plant were counted and weighed individually (following the methodology described by Remmler et al., 2014). The average number and total fresh nodule weight per plant were calculated.

Measurements and statistical analysis

Grain yield (kg ha^{-1}) was standardized to 13% moisture content (www.agrobiznes.md), hectoliter weight (TW, kg hl^{-1}) and thousand-kernel weight (TKW, g) were then measured using standard laboratory procedures. Fat and protein contents (%) were determined using a near-infrared reflectance spectroscopy (NIR) using a Tango spectrophotometer (Bruker Optik GmbH). Plant height was was recorded before harvest on five randomly selected plants from each plot. Combined analysis of variance (ANOVA) in a randomized complete block design (RCBD) was applied to annual treatment means (V1-V7) with year as blocking factor (df error = 12). Mean comparisons were conducted using the Least Significant Difference (LSD) test at the 5% and 1% probability levels, employing critical t-values of $t_{0.05}(12) = 2.179$ and $t_{0.01}(12) = 3.055$, respectively.

RESULTS AND DISCUSSION

Climatic conditions

The three experimental seasons presented sharply contrasting climatic conditions (Tables 3-8). In 2023, a severe spring drought (March-May; May: 33.2 mm vs. 69.4 mm average) was followed by abundant summer rainfall (June: 144.5 mm; August-September: 98.5 and 116.1 mm) and above-average temperatures throughout. This pattern negatively affected early germination and nodule initiation but supported strong vegetative development and seed filling during reproductive stages. In 2024, a prolonged and severe drought dominated the growing season. Precipitation was below average in all key months for soybean development: June (36.2 mm vs. 84.6 mm; -48.4 mm), July (49.0 mm vs. 78.0 mm; -29.0 mm), and August (37.0 mm vs. 56.1 mm;

-19.1 mm). These deficits coincided with the critical periods of flowering, pod setting, and grain filling, severely constraining yield potential across all treatments. Temperatures were above the multiannual average by 1.9-7.6°C in all months, amplifying drought stress through increased evapotranspiration.

In 2025, the most critical climatic event was the severe June drought (22.4 mm vs. 84.6 mm; -62.2 mm), which coincided with soybean flowering at the R1-R2 stages (Fehr and Caviness, 1977), posing a substantial risk to pod initiation and nodulation. This stress was largely alleviated by exceptionally high rainfall in July (150.3 mm vs. 78.0 mm; +72.3 mm), which supported crop recovery during the mid-reproductive stages (R3-R4) (Bayer Crop Science). The above-average temperature in September (+2.1°C) further supported seed filling and contributed to improved final grain quality.

Table 3. Monthly mean air temperature (°C) at Turda, 2023 vs. 65-year average (1958-2023)

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
T mean (°C)	2.8	0.5	6.3	8.8	15.4	19.0	21.8	22.1	19.0	14.0
65yr avg	-3.3	-0.6	4.4	10.0	15.0	18.0	19.8	19.5	15.2	9.8
Deviation	+6.1	+1.1	+1.9	-1.2	+0.4	+1.0	+2.0	+2.6	+3.8	+4.2

Table 4. Monthly precipitation totals (mm) at Turda, 2023 vs. 65-year average

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Prec. (mm)	42.7	27.1	10.8	30.5	33.2	144.5	85.8	98.5	116.1	19.8
65-yr avg	21.7	19.2	24.3	45.6	69.4	84.6	78.0	56.1	42.4	35.4
Deviation	+21.0	+7.9	-13.5	-15.1	-36.2	+59.9	+7.8	+42.4	+73.7	-15.6

Table 5. Monthly mean air temperature (°C) at Turda, 2024 vs. 65-year average

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
T mean (°C)	0.2	7.0	8.8	13.3	15.8	21.7	24.0	23.4	17.9	11.7
65-yr avg	-3.3	-0.6	4.4	10.0	15.0	18.0	19.8	19.5	15.2	9.8
Deviation	+3.5	+7.6	+4.4	+3.3	+0.8	+3.7	+4.2	+3.9	+2.7	+1.9

Table 6. Monthly precipitation totals (mm) at Turda, 2024 vs. 65-year average

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Prec. (mm)	4.8	9.2	37.7	38.8	60.7	36.2	49.0	37.0	64.0	14.0
65-yr avg	21.7	19.2	24.3	45.6	69.4	84.6	78.0	56.1	42.4	35.4
Deviation	-16.9	-10.0	+13.4	-6.8	-8.7	-48.4	-29.0	-19.1	+21.6	-21.4

Table 7. Monthly mean air temperature (°C) at Turda, 2025 vs. 65-year average

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
T mean (°C)	0.3	-0.4	8.3	11.6	13.0	21.8	21.6	20.9	17.3	9.8
65-yr avg	-3.3	-0.6	4.4	10.0	15.0	18.0	19.8	19.5	15.2	9.8
Deviation	+3.6	+0.2	+3.9	+1.6	-2.0	+3.8	+1.8	+1.4	+2.1	0.0

Table 8. Monthly precipitation totals (mm) at Turda, 2025 vs. 65-year average

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Prec. (mm)	5.1	3.8	44.8	31.3	98.6	22.4	150.3	25.2	50.9	56.4
65-yr avg	21.7	19.2	24.3	45.6	69.4	84.6	78.0	56.1	42.4	35.4
Deviation	-16.6	-15.4	+20.5	-14.3	+29.2	-62.2	+72.3	-30.9	+8.5	+21.0

Source: Turda Meteorological Station.

Soil hydrolytic acidity- significance and dynamics

The soil chemical profile at SCDA Turda presents a diagnostic feature of particular agronomic importance for soybean production: near-neutral water pH (6.74-7.78) combined with elevated hydrolytic acidity (Ah = 6.07-6.41 meq/100 g in 2023). This dissociation between active acidity (water pH) and potential acidity (Ah) is characteristic of the clay-illuviated Phaeozems of the Transylvanian Plain. Hydrolytic acidity values above 6.0 meq/100 g indicate that a substantial proportion of the cation exchange capacity is occupied by hydrolytically active H^+ and Al^{3+}, reducing Ca^{2+} saturation of exchange sites and creating suboptimal conditions for soybean root development and rhizobia activity (Haynes and Naidu, 1998; Dumitru et al., 2011).

For soybean, the agronomic consequences of elevated Ah are particularly relevant. Calcium is essential not only for soil aggregate stabilization and root elongation, but also for the early stages of the soybean-*Bradyrhizobium* symbiosis: Ca^{2+} is required for root hair curling, infection thread formation, and bacteroid development within the nodule. Reduced Ca^{2+} saturation of exchange sites therefore directly constrains nodulation efficiency, especially under the rapid early-season soil moisture changes that characterize the Transylvanian Plain (Haynes and Naidu, 1998; White and Broadley, 2003).

Following *Terracalco 95* application, Ah declined dramatically between 2023 and 2024-2025, to 2.43-2.80 meq/100 g in amended plots- a reduction of 55-60% relative to the 2023 baseline. This exceptionally rapid response reflects the very high reactivity of CaO >95%, which hydrates immediately to $Ca(OH)_2$ upon contact with soil moisture, releasing hydroxyl ions that displace acidic cations from the exchange complex. Plots receiving 300 kg ha^{-1} consistently showed the lowest Ah values. The control plot (V1) also showed a natural decline in Ah from 6.41 (2023) to 2.45 meq/100 g (2024), likely reflecting the effect of base cation supply from fertilization; however, Ah in the control remained numerically above the amended plots in all years.

Soil water pH showed much smaller and less consistent treatment effects, remaining between 6.58 and 6.98 across all treatments and years, consistent with the high buffering capacity of these soils. The fact that Ah declined by 55-60% while water pH changed minimally underscores the importance of routinely measuring hydrolytic acidity - not just water pH as the primary soil chemical criterion for guiding calcium amendment decisions on Phaeozem soils of the Transylvanian Plain.

Combined ANOVA- summary

The combined ANOVA summary (Table 9) confirms that the year effect was highly significant ($p<0.001$) for grain yield (F=193.0), MH (F=22.4), MMB (F=100.2), fat (F=34.3), nodule number (F=94.5), and nodule weight (F=22.0).

The exception was protein content, for which neither the year effect (F=1.243; p=0.325) nor the treatment effect (F=1.002; p=0.464) reached significance, reflecting the relatively small year-to-year variation in soybean protein content compared to yield and physical parameters. Treatment effects were not statistically significant at p=0.05 for any trait, though nodule weight (F=2.346; p=0.103) and plant height (F=2.578; p=0.083) showed the strongest treatment F values, approaching significance.

Table 9. Combined ANOVA summary, soybean, ARDS Turda, 2023-2025

Trait	F trt	p	F year	p	LSD 5%	LSD 1%
Grain yield (kg ha^{-1})	0.417	0.854 ns	193.036	<0.001**	254	356
HW (kg hl^{-1})	0.789	0.591 ns	22.359	<0.001**	0.91	1.27
TKW (g)	0.799	0.582 ns	100.178	<0.001**	6.52	9.14
Protein (%)	1.002	0.464 ns	1.243	0.325 ns	2.71	3.81
Fat (%)	0.914	0.517 ns	34.265	<0.001**	1.30	1.83
Nodules/plant (nr)	1.302	0.319 ns	94.451	<0.001**	27	38
Nodule weight (g/pl)	2.346	0.103 ns	21.991	<0.001**	0.96	1.35
Plant height (cm)	2.578	0.083 ns	3.113	0.082 ns	11.55	16.20

RCBD; df trt = 6; df blocks = 2; df error = 12; ** p<0.001; ns p>0.05.
LSD calculated using $t_{0.05}(12) = 2.179$ and $t_{0.01}(12) = 3.055$.

Grain yield- annual results and three-year means

In 2023 (Table 10), V2 (300 kg ha^{-1} before sowing) achieved the highest single-season yield (3,635 kg ha^{-1}, +5.0% vs. V1=3,461 kg ha^{-1}), followed by V3 (3,477 kg ha^{-1}, +0.5%) and V5 (3,502 kg ha^{-1}, +1.2%). The favorable moisture conditions during mid-season 2023 - particularly the abundant June and August-September rainfall - created conditions under which improved soil structure and Ca^{2+} availability from *Terracalco 95* translated into measurable yield advantages for the higher-rate treatments.

Table 10. Yield and quality parameters soybean, ARDS Turda, 2023

Trt	Yield (kg ha^{-1})	HW (kg hl^{-1})	TKW (g)	Fat (%)	Protein (%)
V1	3,461	71.7	170.9	21.9	32.8
V2	3,635	71.3	173.2	21.4	32.9
V3	3,477	71.2	172.0	22.4	30.8
V4	3,421	71.3	172.3	20.3	35.3
V5	3,502	70.9	175.3	20.2	35.8
V6	3,422	71.0	167.5	21.8	32.3
V7	3,459	71.2	168.4	19.4	37.1

Trt - treatment; TW - hectoliter weight; TKW - thousand-kernel weight.

In 2024 (Table 11), the prolonged drought severely depressed yields across all treatments (V1=2,074 kg ha^{-1}). V7 (100 kg ha^{-1} at the 3-5 leaf stage) recorded the highest yield (2,206 kg ha^{-1}, +6.4%), followed by V3 (2,105 kg ha^{-1}, +1.5%) and V5 (2,022 kg ha^{-1}, -2.5%). The relatively better performance of V7 under drought conditions is notable and may reflect the timing of application coinciding with vegetative development, when calcium availability for cell wall reinforcement and root architecture was most critical. V2 (-4.9%) and V6 (-7.1%) yielded below the control, suggesting that the 300 kg ha^{-1} rate may have had initially negative effects on soil solution chemistry under the extremely dry conditions of 2024.

Table 11. Yield and quality parameters soybean, ARDS Turda, 2024

Trt	Yield (kg ha⁻¹)	HW (kg hl⁻¹)	TKW (g)	Fat (%)	Protein (%)
V1	2,074	72.3	142.2	22.2	34.0
V2	1,973	73.7	147.8	21.6	33.8
V3	2,105	72.1	143.7	21.5	33.8
V4	2,017	72.3	146.1	21.3	33.8
V5	2,022	72.4	148.4	22.0	34.3
V6	1,926	73.2	146.2	22.1	35.9
V7	2,206	73.0	143.9	22.2	36.0

Trt - treatment; TW - hectoliter weight; TKW - thousand-kernel weight.

In 2025 (Table 12), V6 (300 kg ha^{-1} at the 3-5 leaf stage) achieved the highest yield (2,671 kg ha^{-1}, +29.0% vs. V1=2,072 kg ha^{-1}), followed by V5 (2,532 kg ha^{-1}, +22.2%) and V4 (2,417 kg ha^{-1}, +16.6%). The strong recovery supported by the exceptional July rainfall after the June drought created conditions where the cumulative soil improvements from two years of *Terracalco 95* application, particularly the reduced Ah and improved aggregate stability-were fully expressed. The high-rate vegetation-stage application (V6) showed the strongest single-season response in 2025, consistent with the importance of calcium availability during the R1-R4 reproductive stages for pod set and seed filling in soybean. Over three years (Table 13), V7 achieved the highest mean (2,689 kg ha^{-1}, +6.0%), closely followed by V5 (2,685 kg ha^{-1}, +5.9%) and V6 (2,673 kg ha^{-1}, +5.4%). All seven treatments exceeded the control numerically.

Table 12. Yield and quality parameters soybean, ARDS Turda, 2025

Trt	Yield (kg ha⁻¹)	HW (kg hl⁻¹)	TKW (g)	Fat (%)	Protein (%)
V1	2,072	73.0	142.4	18.5	33.8
V2	2,321	72.7	145.5	18.4	33.9
V3	2,307	73.3	150.2	19.1	32.6
V4	2,417	73.6	151.3	18.0	34.7
V5	2,532	72.0	149.5	18.9	33.3
V6	2,671	73.2	151.8	18.8	32.4
V7	2,402	72.4	158.2	19.4	31.9

Trt - treatment; TW - hectoliter weight; TKW - thousand-kernel weight.

Table 13. Three-year mean grain yield and LSD groupings, ARDS Turda, 2023-2025

Treatment	Mean (kg ha⁻¹)	vs V1	LSD 5%	LSD 1%
V7: 100 kg ha⁻¹ vegetation (3–5 leaf)	2,689	+6.0%	a	a
V5: 100 kg ha⁻¹ after sowing	2,685	+5.9%	a	a
V6: 300 kg ha⁻¹ vegetation (3–5 leaf)	2,673	+5.4%	a	a
V2: 300 kg ha⁻¹ before sowing	2,643	+4.2%	a	a
V3: 100 kg ha⁻¹ before sowing	2,630	+3.7%	a	a
V4: 300 kg ha⁻¹ after sowing	2,618	+3.3%	a	a
V1 Control	2,536	–	a	a

$LSD_{0.05}$ = 254 kg ha^{-1}; $LSD_{0.01}$ = 356 kg ha^{-1}; same letter - no significant difference.

Despite these consistent advantages, all treatments fell within a single LSD group ($LSD_{0.05}$ = 254 kg ha^{-1}), confirming the absence of statistically significant differences in the combined analysis, a consequence of the large between-year variance (F-year = 193.0) that inflates the error term when year means are used.

Nodulation and plant height

Nodulation data are presented in Tables 14-16. In 2023, V6 (300 kg ha^{-1} during vegetation) recorded the highest nodule number (224 nodules/plant) and V5 the highest nodule weight (6.56 g/plant), both above the control (V1: 193 nodules, 6.05 g/plant). In the drought year 2024, nodule numbers were substantially reduced across all treatments (V1: 101 nodules/plant), but V5 (123 nodules, 5.15 g/plant) and V4 (105 nodules, 5.03 g/plant) consistently outperformed the control. This pattern with after-sowing and low-rate treatments performing relatively better under drought, is consistent with improved early root architecture and Ca^{2+} availability at the critical period of infection thread formation. In 2025, V6 again showed the highest nodule number (109/plant) while V5 recorded the highest weight (5.11 g/plant).

In the combined ANOVA, the year effect was dominant for both nodule number (F=94.5; $p<0.001$) and nodule weight (F=22.0; $p<0.001$). Treatment effects were not significant at p=0.05, but the F value for nodule weight approached significance (F=2.346; p=0.103; $LSD_{0.05}$ = 0.96 g/plant). Pairwise LSD comparison showed V5 (5.61 g/plant) and V4 (5.20 g/plant) numerically highest; V5 differed from V7 (4.20 g/plant) by 1.41 g, exceeding the $LSD_{0.01}$ threshold of 1.35 g/plant, indicating a significant difference for this specific pair.

Plant height showed a consistent numerical response to *Terracalco 95* treatments. In 2023, V4 (105 cm) and V7 (103 cm) exceeded the control (97 cm); in 2024, V4 (103 cm) and V6 (100 cm) were tallest vs. control (77 cm); in 2025, V4 (99 cm) and V6 (98 cm) remained above V1 (80 cm). Three-year means: V4=102.3 cm, V5=95.3 cm, V6=94.7 cm vs. V1=84.7 cm. The consistent advantage of V4 (+17.7 cm vs. control) across all three years suggests that the 300 kg ha^{-1} after-sowing application may be particularly effective at supporting early vegetative development, possibly through improved soil structure in the top 10 cm during the critical seedling establishment phase.

Table 14. Nodulation and soybean height, ARDS Turda, 2023

Trt	Nodules/plant (nr)	Nodule wt (g/plant)	Plant height (cm)
V1	193	6.05	97
V2	176	6.17	102
V3	201	6.44	92
V4	185	5.82	105
V5	173	6.56	98
V6	224	5.21	86
V7	209	5.53	103

Trt - treatment; wt - nodule weight grams per plant.

Table 15. Nodulation and soybean height, 2024

Trt	Nodules/plant (nr)	Nodule wt (g/plant)	Plant height (cm)
V1	101	5.01	77
V2	112	4.11	92
V3	75	3.21	81
V4	105	5.03	103
V5	123	5.15	95
V6	119	4.40	100
V7	87	3.62	83

Trt - treatment; wt - nodule weight grams per plant.

Table 16. Nodulation and soybean height, 2025

Trt	Nodules/plant (nr)	Nodule wt (g/plant)	Plant height (cm)
V1	87	4.12	80
V2	93	3.84	88
V3	81	3.62	85
V4	98	4.75	99
V5	104	5.11	93
V6	109	4.98	98
V7	79	3.44	87

Trt - treatment; wt - nodule weight grams per plant.

Grain quality-HW, TKW, protein and fat

Hectoliter weight (HW) and thousand-kernel weight (TKW) showed no significant treatment effects in the combined analysis (Table 9; MH: F=0.789, p=0.591; TKW: F=0.799, p=0.582). The year effect was highly significant for both (HW: F=22.4; TKW: F=100.2; p<0.001), reflecting the substantially lower kernel weight in the drought-stressed 2024 season (TKW: 142-148 g) compared to 2023 (168-175 g). HW in 2024-2025 (72.0-73.7 kg hl^{-1}) was slightly above 2023 (70.9-71.7 kg hl^{-1}), reflecting denser grain filling in those years despite lower absolute yields.

Protein content showed no significant treatment or year effect in the combined analysis (F-trt=1.002; F-year=1.243; both p>0.30; $LSD_{0.05}$=2.71%). Three-year means ranged from 32.40% (V3) to 35.00% (V7). The high within-year variation in protein across treatments (e.g., 2023: 30.8-37.1%) and the absence of a consistent treatment trend suggest that protein accumulation in soybean (Felix variety) was primarily determined by genotypic factors and seasonal temperature during seed filling rather than by calcium amendment. The exceptionally high protein in V7 and V4 in some years (37.1% and 35.3% in 2023) may reflect concentration effects associated with slightly reduced seed size rather than genuine nutritional improvement.

Fat content was not significantly influenced by treatment (F=0.914; p=0.517; $LSD_{0.05}$ = 1.30%). The year effect was highly significant (F=34.3; p<0.001), driven by the markedly lower fat content in 2025 (18.0-19.4%) compared to 2023 (19.4-22.4%) and 2024 (21.3-22.2%).

This year-to-year variation in fat content is consistent with the known sensitivity of soybean lipid accumulation to temperature and radiation during seed filling factors, that differed substantially across the three experimental seasons. Numerically, V3

(21.00%) and V6 (20.90%) showed slightly higher three-year mean fat than the control (20.87%), while V4 (19.87%) and V7 (20.33%) were somewhat lower. According to the findings of Șimon et al. (2025) fat accumulation in soybean seeds is primarily determined by environmental conditions during the grain-filling period.

ANOVA tables- individual traits

SS (sum of squares), df (degrees of freedom), and MS (mean square) are presented for the ANOVA. Significance levels are indicated as ns (p>0.05), * (p<0.05), and ** (p<0.001). A combined ANOVA based on a randomized complete block design (RCBD) was applied, with error df = (t–1) (b–1) = 12.

Table A1. ANOVA - grain yield (kg ha^{-1})

Source	df	SS	MS	F	P
Treatments (V1-V7)	6	51,031.90	8,505.32	0.417	0.854 ns
Years (blocks)	2	7,877,959.14	3,938,979.57	193.036	<0.001**
Error (Trt × Year)	12	244,865.52	20,405.46		
Total	20	8,173,856.57			

Table A2. ANOVA - lectoliter weight (HW, kg hl^{-1})

Source	df	SS	MS	F	P
Treatments	6	1.23	0.21	0.789	0.591 ns
Years (blocks)	2	11.63	5.81	22.359	<0.001**
Error	12	3.12	0.26		
Total	20	15.98			

Table A3. ANOVA - thousand-kernel

Source	df	SS	MS	F	P
Treatments	6	64.42	10.74	0.799	0.582 ns
Years (blocks)	2	2,691.26	1,345.63	100.178	<0.001**
Error	12	161.19	13.43		
Total	20	2,916.87			

Table A4. ANOVA - thousand-kernel

Source	df	SS	MS	F	P
Treatments	6	14.00	2.33	1.002	0.464 ns
Years (blocks)	2	5.79	2.89	1.243	0.325 ns
Error	12	27.94	2.33		
Total	20	47.73			

Table A5. ANOVA - fat content (%)

Source	df	SS	MS	F	P
Treatments	6	2.94	0.49	0.914	0.517 ns
Years (blocks)	2	36.72	18.36	34.265	<0.001**
Error	12	6.43	0.54		
Total	20	46.09			

Table A6. ANOVA - nodule number per plant

Source	df	SS	MS	F	p
Treatments	6	1,807.24	301.21	1.302	0.319 ns
Years (blocks)	2	43,688.67	21,844.33	94.451	<0.001**
Error	12	2,775.33	231.28		
Total	20	48,271.24			

Table A7. ANOVA - nodule weight (g/plant)

Source	df	SS	MS	F	P
Treatments	6	4.10	0.68	2.346	0.103 ns
Years (blocks)	2	12.81	6.41	21.991	<0.001**
Error	12	3.50	0.29		
Total	20	20.41			

Table A8. ANOVA - plant height (cm)

Source	df	SS	MS	F	P
Treatments	6	652.48	108.75	2.578	0.083 ns
Years (blocks)	2	262.57	131.29	3.113	0.082 ns
Error	12	506.10	42.18		
Total	20	1,421.14			

SS - sum of squares; df - degrees of freedom; MS - mean square; ns - not significant (p>0.05); * p<0.05; ** p<0.001.RCBD combined analysis; error df= (t–1)(b–1)= 12.

CONCLUSIONS

The most consistent finding of this three-year experiment was the dramatic reduction in soil hydrolytic acidity (Ah) following *Terracalco 95* application from 6.07-6.41 meq/100 g (2023) to 2.43-2.80 meq/100 g (2024-2025), a decline of 55-60% achieved despite minimal changes in water pH (6.58-6.98). This confirms that *Terracalco 95* effectively neutralises potential acidity in Phaeozem soils of the Transylvanian Plain, improving Ca^{2+} saturation of exchange sites and creating more favourable conditions for soybean root development and rhizobial symbiosis.

Combined ANOVA confirmed highly significant year effects (p<0.001) for yield, physical quality, fat, and nodulation traits, with treatment effects not reaching statistical significance at p= 0.05 for any trait. Nonetheless, all Terracalco treatments numerically exceeded the control in three-year mean yield (+3.3% to +6.0%), with V5 (100 kg ha^{-1} after sowing, +5.9%) and V7 (100 kg ha^{-1} at the 3-5 trifoliate leaf stage, +6.0%) showing the most consistent performance. The largest single-season yield increases were recorded in 2025 for V6 (+29.0%) under conditions where cumulative soil improvement combined with mid-season moisture recovery allowed full expression of the amendment effect.

Nodule weight showed the highest treatment F value among all traits (F=2.346; p=0.103), and a specific pairwise comparison (V5 vs. V7) exceeded the $LSD_{0.01}$ threshold, suggesting biologically relevant effects on symbiotic nitrogen fixation that warrant further investigation with full within-year replication. Plant height showed a consistent numerical advantage for V4 (300 kg ha^{-1} after sowing; +17.7 cm over control across three years), indicating improved early vegetative development. The application of *Terracalco 95* at 100-300 kg ha^{-1} is recommended as a soil conditioning strategy for soybean production on moderately acid

Phaeozem soils of the Transylvanian Plain. Routine monitoring of hydrolytic acidity alongside water pH is essential for guiding amendment decisions on these soils.

ACKNOWLEDGEMENTS

The authors thank Carmeuse Europe S.A. for providing *Terracalco 95* and supporting the field research, the ARDS Turda team for all experimental operations during 2023-2025, and OSPA Alba Iulia for conducting the soil analyze.

REFERENCES

Barșon, G., Șopterean, L., Suciu, L.A., Crișan, I., Duda, M.M., 2021. *Evaluation of Agronomic Performance of Maize (Zea mays L.) under a Fertilization Gradient in Transylvanian Plain*. Agriculture, 11(9), 896. https://doi.org/10.3390/agriculture11090896

Brady, N.C., and Weil, R.R., 2008. *The Nature and Properties of Soils*. 14th ed. Prentice Hall, Upper Saddle River: 246-289.

Chețan, F., 2019. *The influence of the tillage system and the crop rotation on the soil availability in the main nutrients and the yields obtained in Turda area*. International Agronomy, LXII(1): 19-23. https://agronomyjournal.usamv.ro/pdf/2019/issue_1/Art2.pdf

Chețan, F., Șimon, A., Călugăr, R.E., Urdă, C., Rezi, R., Popa, A., Ceclan, A., Chețan, C., Bărdaș, M., 2026. *Influence of soil tillage system and fertilization on soil compaction, water reserve and soybean yield*. Romanian Agricultural Research, 43: 49-56. https://doi.org/10.59665/rar4305

Dumitru, M., Calciu, I., Cârstea, S., Pîrvan, M., 2011. *Starea solurilor din România*. ICPA, București: 45-62.

Fehr, W.R., and Caviness, C.E., 1977. *Stages of soybean development*. Special Report 80, Iowa Agricultural Experiment Station, Iowa Cooperative External Series, Iowa State University, Ames.

Feller, C., Bleiholder, H., Buhr, L., Hack, H., Hess, M., Klose, R., Meier, U., Stauss, R., van den Boom, T., Weber, E., 1995. *Phänologische Entwicklungsstadien von Gemüsepflanzen*: *II. Fruchtgemüse und Hülsenfrüchte*. Nachrichtenbl. Deut. Pflanzenschutzd., 47: 217-232.

Haynes, R.J., and Naidu, R., 1998. *Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review*. Nutrition Cycling in Agroecosystems, 51: 123-137.

Kabala, C., and Jedrzejewski, S., 2024. *Comparison of cation exchange capacity extraction methods for soil data harmonization and soil classification in Central and East Europe*. Geoderma, 450, 117044. https://doi.org/10.1016/j.geoderma

Lăcătușu, R., Lăcătușu, A.R., Lungu, M., Avarvarei, B.V., 2016. *Soil amendments with calcium-based products in Romanian arable land*. Romanian Agricultural Research, 33: 101-111.

Remmler, L., Clairmont, L., Rolland-Lagan, A.G., Guinel, F.C., 2014. *Standardized mapping of nodulation patterns in legume roots.* New Phytol., 202: 1083-1094. https://doi.org/10.1111/nph.12712

Singh, G., Ratnaparkhe, M., Kumar, A., 2019. *Comparative analysis of transposable elements from Glycine max, Cajanus cajan and Phaseolus vulgaris*. J. Expl. Biol. Agricul. Sci., 7(2): 167-177.

Sprent, J.I., Ardley, J., James, E.K., 2017. *Biogeography of nodulated legumes and their nitrogen-fixing symbionts*. New Phytol., 215(1): 40-56. doi: 10.1111/nph.14474

Șimon, A., Chețan, F., Popa, A., Ceclan, A., Popa, A., Urdă, C., Tritean, N., Rezi, R., Russu, F., Negrea, A., 2025. *Improving soybean quality parameters by sowing on different dates in various climatic years*. Scientific Papers, Series A, Agronomy, LXVIII(1): 631-639. https://agronomyjournal.usamv.ro/pdf/2025/issue_1/Art78.pdf

Urdă, C., Șimon, A., Chețan, F., Popa, A., Ceclan, C., Leonte, A., 2026. *Yield and quality of soybean crop under the influence of tillage systems*. Romanian Agricultural Research, 43: 473-481. https://doi.org/10.59665/rar4341

White, P.J., and Broadley, M.R., 2003. *Calcium in plants*. Annals of Botany, 92: 487-511.

*** Romanian Soil Taxonomy System (SRTS), 2012.

*** Meteorological Station Turda longitude: 23°47, latitude: 46°35’, altitude: 427 m.

*** Tango Bruker Optik GmbH, Rudolf-Plank-Str. 27, 76275 Ettlingen.

*** ANOVA. PolyFact and Duncan’s Test PC Program for Variant Analyses Made for Completely Randomized Polyfactorial Experiences; USAMVCluj-Napoca, Romania, 2015.

*** https://agrobiznes.md/cum-se-recolteaza-si-pastreaza-corect-soia.html

*** Bayer Crop Science, https://www.cropscience.bayer.us/articles/bayer/soybean-growth-stages (Accessed on 12 May 2026).