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Soybean yield and grain protein concentration in different soil managements

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Abstract – The objective of this work was to evaluate the effects of soil management on soybean grain yield and grain protein and oil concentrations, in long-term experiments. Data from three long-term experiments conducted in Londrina, in the state of Paraná, Brazil, were analyzed in two growing seasons with different water availabilities. Grain yield was higher in the no-tillage system (NTS) compared with treatments with soil mobilization (3,972 kg ha^{-1} vs 3,421 kg ha^{-1} in the 2022/2023 season and 2,468 kg ha^{-1} vs 2,043 kg ha^{-1} in the 2023/2024). Grain protein concentration was also higher in treatments under NTS compared to treatments with soil mobilization (382 g kg^{-1} vs 370 g kg^{-1} in the 2022/2023 season and 382 g kg^{-1} vs 371 g kg^{-1} in the 2023/2024). Grain oil concentration was lower in the treatments under NTS , when compared with those with soil mobilization (217 g kg^{-1} vs 222 g kg^{-1} in the 2022/2023 season and 215 g kg^{-1} vs 222 g kg^{-1} in the 2023/2024). NTS reconciles a greater soybean grain yield with a higher grain protein concentration.

Index terms: *Glycine max*, conservationist agriculture, conventional tillage, grain composition.

Produtividade e concentração de proteína no grão de soja em diferentes manejos de solo

Resumo – O objetivo deste trabalho foi avaliar os efeitos do manejo do solo na produtividade e na concentração de proteína e óleo nos grãos de soja, em experimentos de longo prazo. Dados de três experimentos de longa duração conduzidos em Londrina, no estado do Paraná, Brasil, foram analisados em duas safras com diferentes disponibilidades hídricas. A produtividade de grãos foi maior no sistema plantio direto (SPD) em comparação aos tratamentos com mobilização do solo (3.972 kg ha^{-1} vs 3.421 kg ha^{-1} na safra 2022/2023 e 2.468 kg ha^{-1} vs 2.043 kg ha^{-1} na safra 2023/2024). A concentração de proteína nos grãos também foi maior nos tratamentos em SPD, comparativamente aos tratamentos com mobilização do solo (382 g kg^{-1} vs 370 g kg^{-1} na safra 2022/2023 e 382 g kg^{-1} vs 371 g kg^{-1} na safra 2023/2024). A concentração de óleo nos grãos foi menor nos tratamentos em SPD, quando comparados aos com mobilização do solo (217 g kg^{-1} vs 222 g kg^{-1} na safra 2022/2023 e 215 g kg^{-1} vs 222 g kg^{-1} na safra 2023/2024). O SPD concilia maior produtividade de soja com maior concentração de proteínas no grão.

Termos para indexação: *Glycine max*, agricultura conservacionista, preparo convencional do solo, composição do grão.

Introduction

The industrial processing of soybeans primarily targets oil extraction with the resulting meal holding high commercial value due to its protein concentration and amino acid composition (Assefa et al., 2018). The soybean grain protein concentration has declined over the years, while oil content has currently increased, as observed in major soybean-producing nations Brazil (Umburanas et al., 2022) and the United States (Reis et al., 2020). This shift presents a significant challenge for soybean meal industries, which are increasingly struggling to achieve the industry standard of at least 460 g kg^{-1} protein (Pope et al., 2023).

Soybean grain composition and yield are influenced by genetics, environment, and management practices, in addition to their complex interactions. However, the precise contribution of these interactions to grain composition remains poorly understood (Assefa et al., 2019). Furthermore, soybean grain composition is also affected by specific management practices, including fertilization, planting date, row spacing, seeding rate, and crop rotation (Bellaloui et al., 2011, 2020; Houx III et al., 2014; Mourtzinis et al., 2017; Assefa et al., 2019; Balbinot Junior et al., 2024).

Soil mobilization alters its physical, chemical, and biological attributes (Peixoto et al., 2020; Pellissier et al., 2024). Additionally, water availability and soil temperature affect residual biomass on the soil surface, which in turn impact plant nutrition and the biological nitrogen fixation (BNF) process in soybean plants (Ciampitti et al., 2021). Despite these known effects, the specific impacts of soil management on soybean grain composition, such as grain protein and oil concentration, remain insufficiently reported in the literature (Houx III et al., 2014).

In Brazil, soybean crops are typically grown under no-tillage system (NTS), which provides several advantages, including reduced erosion, increased yields, and production stability (Fuentes-Llanillo et al., 2021). Given this context, soybeans may exhibit a higher grain protein concentration compared to those grown in soils with a history of mobilization. This is primarily attributed to enhanced BNF (Torabian et al., 2019; Virk et al., 2024), and more favorable soil physical conditions for soybean growth (Moraes et al., 2016).

The objective of this work was to evaluate the effects of soil management on soybean grain yield, as well as grain protein and oil concentrations, in long-term experiments.

Materials and Methods

This study evaluated three long-term experiments conducted in the municipality of Londrina, Paraná State, Brazil (23°11'S and 51°11'W, at 630 m of altitude) from 1981 to 2023. The soil at the experiment site is classified as Latossolo Vermelho Eutroférrico according to the Brazilian Soil Classification System (Santos et al., 2018), which is similar to Clayey Rhodic Eutrudox (Soil Survey Staff, 2014), which comprises 782 mg dm^{-3} clay, 159 mg dm^{-3} silt, and 59 mg dm^{-3} sand. The regional climate is Cfa according Köppen classification.

For the three experiments, the soybean cultivars used were BRS 2560XTD in the 2022/2023 season and BRS 1061IPRO in the 2023/2024 season. BRS 2560XTD cultivar is an indeterminate growth type with a relative maturity group 6.0. Its average grain protein is 381 g kg^{-1} and its average oil concentration is 208 g kg^{-1}, and it has a 1000-grain weight of 188 g (BRS… 2023). BRS 1061IPRO cultivar, also an indeterminate growth type, has a relative maturity group 6.1. Its average grain protein and oil concentration are 368 g kg^{-1} and 229 g kg^{-1} on a dry-weight basis, respectively, and a 1000-grain weight of 171 g (BRS… 2023). In all three experiments, soybean seeds received a treatment consisting of fungicides [pyraclostrobin (0.025 kg a.i. 100 kg^{-1} seed) + thiophanate methyl (0.225 kg a.i. 100 kg^{-1} seed)], an insecticide (fipronil, 0.25 kg a.i. 100 kg^{-1} seed), and an inoculant containing *Bradyrhizobium elkanii* strains SEMIA 587 and SEMIA 5019 (2 mL kg^{-1}).

The first long-term experiment (Experiment I) began in 1981, employing a completely randomized block design with four replicates. Each plot measured 8 m × 50 m (400 m^2), with a usable harvest area for soybeans of 1.35 m × 48.00 m (64.80 m^2). Since its implementation, the experiment has maintained a succession of wheat (*Triticum aestivum* L.) in the winter and soybeans in the summer. The treatments consisted of four soil management procedures, performed annually before soybean sowing: no-tillage system (NTS); conventional tillage system (CTS), involving annual plowing (26-inch disc plow, average depth of 0.22 m) followed by two harrowings; annual

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scarification, utilizing a five-shank scarifier (spaced 0.35 m apart, average depth of 0.22 m) followed by one harrowing; and annual heavy harrowing, performed with a heavy harrow (24-inch discs, average depth of 0.12 m) followed by one harrowing.

In winter, preceding wheat sowing, all treatments, except NTS, underwent soil preparation involving heavy harrowing followed by light harrowing. Wheat was then sown using a tractor-mounted seeder-fertilizer equipped with offset double-disc furrowers for both fertilizer and seed, with rows spaced at 0.17 m apart. Soybean sowing was carried out using a tractor-driven seeder-fertilizer equipped with furrowing rods until the 1999/2000 season, and a guillotine system from the 2000/2001 season onward. Both methods utilized offset double-disc seed furrowers, with rows spaced 0.45 m apart. In each season, all plots received identical fertilizer applications determined by soil analysis and crop-specific recommendations. Soybean sowing occurred on October 24, 2022, and October 11, 2023.

The second long-term experiment (Experiment II) started in 1992 and also used a completely randomized block design with four replicates. Plots measured 7 m × 38 m (266 m^2), with a usable harvest area for soybeans of 1.35 m × 36.00 m (48.60 m^2). This experiment evaluated three distinct soil management systems: NTS established in 1992, NTS established in 2003, and CTS established in 1992. For the conventional annual tillage treatments, plowing was performed in the summer, followed by harrowing, consistently since 1992. All plots received identical fertilizer applications each season, based on soil analysis and the crop-specific recommendations. Soybean sowing dates for the experiment were October 24, 2022, and October 23, 2023.

The third long-term experiment (Experiment III) began in 1988, and utilized a randomized complete block design with four replicates. Each plot measured 7.5 m × 30.0 m (225.0 m^2), with a usable area of 1.35 m × 28.00 m (37.80 m^2). This experiment investigated seven distinct tillage systems: NTS established in 1988; NTS established in 2001; chiseling every three years; CTS every two years; CTS every year; chiseling every year; and heavy harrow every year. All plots received identical fertilizer applications each season based on soil analysis and crop-specific recommendations. Soybean sowing dates for this experiment were October 25, 2022, and October 11, 2023.

Following the mechanized harvest of the plants in each plot's usable area, soybean grain yield was estimated and expressed in kg ha^{-1}, adjusted to 13% moisture. Whole-grain oil and protein concentrations were determined by near-infrared reflectance spectroscopy (Heil, 2010). Clean whole grains were analyzed in triplicate, using an Antaris II FT-NIR analyzer (Thermo Fisher Scientific, Waltham, MA, USA) equipped with an integrating sphere at a resolution of 4 cm^{-1}, with an average of 32 scans and background correction at each reading. Protein and oil concentrations were estimated using mathematical models: protein model utilized 180 standards ($r = 0.97$; RMSEC = 0.64), and oil model used 170 standards ($r = 0.98$, RMSEC = 0.45). All results were expressed on a dry-weight basis (Oliveira et al., 2018). Protein and oil yields were calculated based on the determined grain yield, as well as protein and oil concentrations.

Meteorological data for both growing seasons were obtained from the Embrapa Soja meteorological station, located 500 to 800 m from the experimental sites (Figure 1). The water balance was calculated using the Thornthwaite & Mather (1955) method. During the 2022/2023 season, there was no significant water deficit experienced throughout the soybean development cycle (Figure 1 A). In contrast, the 2023/2024 season was characterized by an intense water deficit, particularly in December, January, and early February. This period coincided with crucial soybean developmental stages, including full flowering and the beginning of grain filling (Figure 1 C). Generally, temperatures were also higher in the 2023/2024 season compared to the 2022/2023 season (Figure 1 B and D).

Data from each growing season were analyzed separately. First, Shapiro-Wilk's test was applied to check the normality of residuals, and Bartlett's test was used to assess the homogeneity of variances. These tests confirmed that data transformation was not required, as the dataset met the assumptions for analysis of variance (ANOVA). Subsequently, data were subjected to the F-test ($p \leq 0.05$). When the effects of experimental factors were significant, the Least Significant Difference (LSD) test was used for mean comparisons ($p \leq 0.05$). Additionally, the data underwent Pearson linear correlation analysis ($p \leq 0.05$). All statistical analysis were performed using R software (R Core Team, 2013).

Results and Discussion

In all three experiments and across both growing seasons, soybean yield differed among soil management treatments (Table 1). In Experiment I, soybean yield was consistently higher under NTS compared to the three treatments involving soil mobilization in both seasons. For Experiment II, NTS treatments presented higher soybean yield (+41%) than the CTS in both seasons. In Experiment III, treatments that included soil mobilization showed the lowest soybean yield in both seasons.

Tillage effects on crop yields are highly dependent on several interacting factors, including climate, soil characteristics, crop types, cropping system interactions, cultivars, management practices, and water availability during the growing season (Franchini et al., 2012; Dou et al., 2024), which leads to discrepancies in experimental results. Consistent with this, the findings showed a greater soybean grain yield under NTS, even with different establishment times, compared to soil management practices involving soil mobilization, across all three experiments and both seasons.

In the 2022/2023 season, characterized by no significant water deficit (Figure 1 A), the average soybean yield for the NTS treatment across the three experiments was 16% higher than those treatments involving soil mobilization. In contrast, during the 2023/2024 season, which experienced a significant water deficit (Figure 1C), the NTS treatment average of the three experiments was 21% higher than the average of the treatments with soil mobilization. These findings corroborate previous reports indicating that the benefits of NTS on soybean yield are more pronounced under conditions of lower water availability, particularly during the crop's reproductive phase (Franchini et al., 2012; Mertz-Henning et al., 2018).

A study by Silva et al. (2023a) carried out in a tropical region of Brazil concluded that long-term NTS, maintained for 33 years, reduces the risk of water stress for soybean plants, contributing to higher grain yields compared to the CTS. Similarly, in a global analysis of eight growing seasons in Southern Brazil, Silva et al.

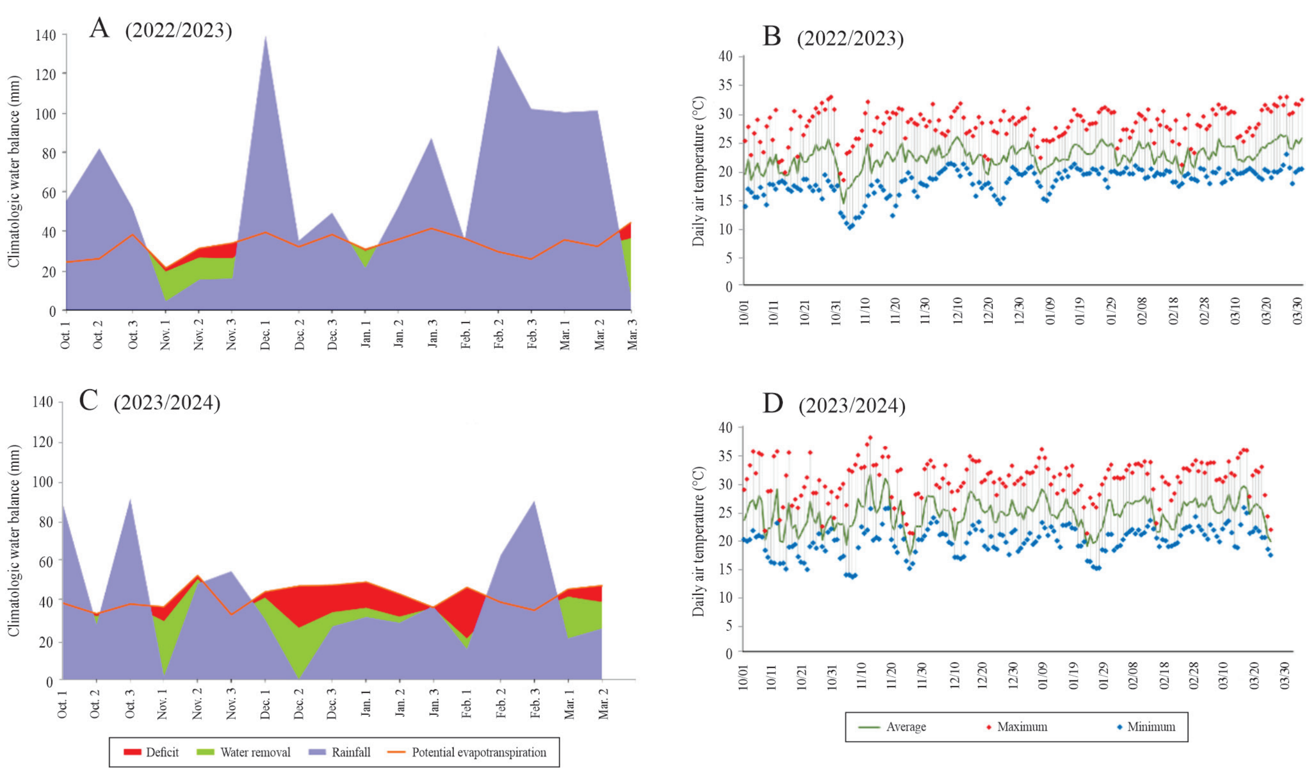

Figure 1. Climatologic water balance according to the method described by Thornthwaite & Mather (1955) and daily air temperature in two soybean growing seasons, 2022/2023 (A and B) and 2023/2024 (C and D).

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Table 1. Soybean yield in distinct soil management systems across three experiments and two growing seasons(1).

Soil management	Soybean yield (kg ha^{-1})	
	2022/2023	2023/2024
	Experiment I	
No-tillage	4,378a	2,212a
Conventional tillage	3,606b	1,662b
Chiseling	3,694b	1,771b
Heavy harrow	3,372b	1,369b
CV (%)	8	16
	Experiment II	
No-tillage (established in 1992)	3,652a	2,584a
No-tillage (established in 2003)	3,608a	2,456a
Conventional tillage	2,349b	1,991b
CV (%)	10	12
	Experiment III	
No-tillage (established in 1988)	4,167a	2,568a
No-tillage (established in 2001)	4,057a	2,520ab
Chiseling every 3 years	4,045a	2,602a
Conventional tillage every 2 years	2,997b	2,077c
Conventional tillage	2,954b	2,099c
Chiseling	4,055a	2,531ab
Heavy harrow	3,722a	2,291bc
CV (%)	12	11

(1)Means followed by equal letters, in the columns, do not differ from each other by the Least Significant Difference test, at 5% probability.

(2023b) found that soybean yield under NTS was, on average, 6% greater than with CTS.

In Experiments I and II, soybean grain protein concentration was lower in CTS in both seasons (Table 2). For Experiment III, a similar trend emerged in the 2022/2023 season, with lower protein concentration observed in CTS treatments compared with NTS treatments. However, no significant differences in protein concentration were observed among treatments during the 2023/2024 season. Regarding protein yields, NTS showed the highest yields in Experiments I and II in both seasons (Table 3). Conversely, in Experiment III, in both seasons, the lowest protein yields were observed in CTS treatments during both seasons.

The results of this study support the positive effects of NTS on soybean grain protein concentrations in both seasons, despite differing water availability conditions. This aligns with findings from a long-term experiment by Temperly & Borges (2006), in which a reduction in grain protein concentration was reported under CTS, while it remained constant under NTS. Such corroborating evidence suggests that the widespread adoption of NTS in Brazil over recent

Table 2. Soybean seed protein and oil concentration on a dry-weight basis in different soil management systems across three experiments and two growing seasons(1).

Soil management	Protein concentration (g kg^{-1})		Oil concentration (g kg^{-1})	
	2022/2023	2023/2024	2022/2023	2023/2024
		Experiment I		
No-tillage	381a	396a	214b	215a
Conventional tillage	367b	364b	226a	232a
Chiseling	367b	373ab	227a	226a
Heavy harrow	371ab	374ab	218b	222a
CV (%)	2	5	2	6
		Experiment II		
No-tillage (established in 1992)	382a	383a	218b	215b
No-tillage (established in 2003)	383a	378a	220b	219b
Conventional tillage	350b	365b	228a	230a
CV (%)	3	4	3	4
		Experiment III		
No-tillage (established in 1988)	379a	374a	220abc	216ab
No-tillage (established in 2001)	384a	379a	215bc	209b
Chiseling every 3 years	385a	369a	213c	223a
Conventional tillage every 2 years	365b	373a	222a	217ab
Conventional tillage	363b	373a	221ab	218ab
Chiseling	384a	373a	218abc	216ab
Heavy harrow	376a	373a	222abc	215ab
CV (%)	2	4	4	5

(1)Means followed by equal letters, in the columns, do not differ from each other by the Least Significant Difference test, at 5% probability.

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decades may have helped attenuate the reduction in soybean protein concentration, a phenomenon often attributed primarily to genetic changes (Umburanas et al., 2022).

The positive effects of NTS on soybean grain protein concentration can be attributed to several associated factors, primarily linked to the availability of mineral nitrogen (N) in the soil and the establishment of optimal conditions for the full functioning of BNF. Indeed, N deficiency reduces the remobilization of this crucial nutrient from vegetative organs to soybean grains (La Menza et al., 2020). Estimates indicate that each megagram (Mg) of soybean grains contains 50 to 66 kg of N, with approximately 80% of this N originating from BNF and the remaining 20% derived from mineralized N in soil organic matter (Hungria & Mendes, 2015; Cordeiro & Echer, 2019).

Ciampitti & Salvagiotti (2018) reported that the contribution of soil mineral N to soybean nutrition can range from 28% to 56%. Plausibly, BNF efficiency in soybean crops grown under NTS is associated with higher protein concentrations in the grains (Virk et al., 2024). However, further research is needed to fully elucidate the precise mechanisms involved in the enhanced protein concentration in soybean grains under NTS compared to management practices that involve soil mobilization.

Grain oil concentration showed varied responses across experiments and seasons (Table 2). In Experiment I, during the 2022/2023 season, a higher oil concentration was observed in CTS and chiseling treatments, whereas no differences were detected among treatments in the 2023/2024 season. In Experiment II, CTS exhibited higher grain oil concentration than NTS treatments in both seasons. For Experiment III, the NTS established in 2001 presented the lowest grain oil concentrations in both seasons.

Regarding oil yield, in Experiment I, it was higher under NTS than in heavy harrow treatment in both seasons (Table 3). In Experiment II, NTS treatments resulted in higher oil yield compared to CTS treatments, and, in Experiment III, CTS presented the lowest oil yield. Thus, although NTS presented lower grain oil concentrations compared to CTS, the overall oil yield per area was not compromised, which can be attributed

Table 3. Soybean protein and oil yield in different soil management systems in three experiments, and two growing seasons[(1)].

Soil management	Protein yield (kg ha^{-1})		Oil yield (kg ha^{-1})	
	2022/2023	2023/2024	2022/2023	2023/2024
	Experiment I			
No-tillage	1,667a	859a	937a	476a
Conventional tillage	1,322b	622b	817b	382ab
Chiseling	1,354b	682b	837ab	400a
Heavy harrow	1,254b	515b	734b	301b
CV (%)	9	18	9	16
	Experiment II			
No-tillage (established in 1992)	1,396a	990a	798a	554a
No-tillage (established in 2003)	1,384a	932a	795a	536a
Conventional tillage	826b	728b	534b	457b
CV (%)	12	14	11	12
	Experiment III			
No-tillage (established in 1988)	1,579a	958a	918a	552ab
No-tillage (established in 2001)	1,559ab	954a	873a	530ab
Chiseling every 3 years	1,560ab	961a	862a	580a
Conventional tillage every 2 years	1,096c	776b	665b	450c
Conventional tillage	1,077c	783b	652b	457c
Chiseling	1,563ab	942a	883a	548ab
Heavy harrow	1,400b	858ab	816a	494bc
CV (%)	12	11	13	12

[(1)]Means followed by equal letters, in the columns, do not differ from each other by the Least Significant Difference test, at 5% probability.

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to the higher grain yield achieved under NTS when compared to treatments involving soil mobilization.

A positive correlation was observed between soybean yield and protein concentration in the present study (Table 4). This aligns with Mourtzinis et al. (2017), who also reported positive correlations between grain yield and protein concentration (r = 0.20) and between grain yield and oil concentration (r = 0.40).

In contrast, other studies have reported different associations. Assefa et al. (2018), in a spatial characterization study of soybean yield and quality, found a weak negative correlation coefficient (r = -0.10) for grain yield and protein concentration. Furthermore, analyzing a wide range of data, the same authors obtained a negative relationship between protein concentration and grain yield. Rowntree et al. (2013) observed contrasting correlations between grain yield and both protein and oil concentrations when comparing planting seasons and maturity groups.

Table 4. Correlation coefficients among grain yield, protein concentration, and oil concentration across three experiments and two growing seasons.

Variable	Soybean yield	Protein concentration
	Experiment 1 (2022/2023)	
Soybean yield	1.00	
Protein concentration	0.48*	1.00
Oil concentration	-0.31ns	-0.72*
	Experiment 1 (2023/2024)	
Soybean yield	1.00	
Protein concentration	0.60*	1.00
Oil concentration	-0.43*	-0.80*
	Experiment 2 (2022/2023)	
Soybean yield	1.00	
Protein concentration	0.80*	1.00
Oil concentration	-0.47*	-0.74*
	Experiment 2 (2023/2024)	
Soybean yield	1.00	
Protein concentration	0.57*	1.00
Oil concentration	-0.59*	-0.59*
	Experiment 3 (2022/2023)	
Soybean yield	1.00	
Protein concentration	0.63*	1.00
Oil concentration	-0.33*	-0.59*
	Experiment 3 (2023/2024)	
Soybean yield	1.00	
Protein concentration	-0.09ns	1.00
Oil concentration	-0.02ns	-0.72*

*Significant at 5% probability. nsNonsignificant at 5% probability.

The correlation between yield and protein concentration can lead to an interpretation that yields are always inversely related to quality when this is not the case. Additionally, negative correlations were observed between the concentration of protein and oil in the seeds. As discussed by Mertz-Henning et al. (2018) and Assefa et al. (2019), generally, there is a negative correlation between protein and oil concentration in soybean seeds. In this context, NTS treatments conferred higher protein concentrations and lower oil concentrations in soybean grains compared to treatments involving soil mobilization. This is particularly significant, as protein is considered the most valuable constituent of soybeans for industrial purposes.

Conclusions

1. The no-tillage system consistently provides greater soybean (*Glycine max*) grain yield compared to soil management systems that involve mobilization.
2. The no-tillage system provides higher grain protein concentration and a lower grain oil concentration in soybeans compared to management systems that involve soil mobilization.

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No generative artificial intelligence (AI) was used in this study.

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The authors declare no conflicts of interest.

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