

Article

Effects of Foliar Application on Soybean Yield and Quality Traits

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Abstract

Adequate fertilization is essential for optimizing soybean productivity and seed quality, while supplementary fertilization plays a key role in correcting nutrient deficiencies and supporting plant performance under varying environmental conditions. This study evaluated the effects of the foliar application of macro- and micronutrients enriched with free amino acids and *Ascophyllum nodosum* extract applied at two phenological stages—six fully developed trifoliolate leaves (V6) and beginning flowering (R1)—on soybean grain yield, protein content and oil content. Experiments were conducted over two growing seasons at ARDS Turda, Romania, using a randomized complete block design with three replications to compare three fertilization treatments: basic mineral fertilization (control), mineral fertilization supplemented with foliar application at the V6 vegetative stage, and mineral fertilization supplemented with foliar application at the R1 reproductive stage. Basic fertilization was performed before sowing using granulated nitroclacium at a rate of 100 kg ha⁻¹. Foliar fertilization included Naturamin WSP applied at a rate of 0.5 kg ha⁻¹ and Pleniflor and Naturfruit at a rate of 2 L ha⁻¹. Foliar fertilization at the V6 stage significantly improved grain yield in most cultivars, with increases ranging from 1% to 18%, particularly in the 000 and 00 maturity groups (MGs). Across the maturity groups, the highest average yields were recorded in MG 0 cultivars (up to 2845 kg ha⁻¹). In contrast, foliar application at the R1 stage was more effective in increasing seed protein content, with improvements of up to 11% in early maturity cultivars. Oil content showed only minor and inconsistent responses, with maximum increases of 4% depending on genotype. Linear Discriminant Analysis (LDA) revealed that environmental conditions and genotype explained most of the observed variation (Axis 1 = 89.91%, Axis 2 = 7.79%), indicating that cultivar response to foliar fertilization was strongly influenced by genotype × environment interactions. The effectiveness of foliar fertilization depends on application timing, cultivar maturity group and environmental conditions.

Keywords: foliar fertilizers; soybean productivity; seeds quality; plant development



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1. Introduction

Soybean (*Glycine max* (L.) Merrill) represents a major component of global food security due to its high protein and oil content, as well as its ability to biologically fix atmospheric nitrogen [1] through symbiosis with bacteria belonging to the genus *Rhizobium*. Despite its numerous agronomic and nutritional advantages, successful soybean cultivation depends on several agronomic factors [2], including genotype selection and the interaction between cultivars and environmental conditions [3]. These studies emphasize that maximizing

soybean productivity is possible only when cultivars are properly adapted to regional environmental conditions [4].

Since agricultural land resources are limited, increasing crop productivity per unit area has become essential to meet the demands of the continuously growing human population [5]. Rational fertilization practices can enhance the productive potential of soybean cultivars [6], maintain a higher leaf area index, improve light energy use efficiency during the middle and late growth stages, and delay leaf senescence [7].

Nitrogen is considered one of the most important nutrients influencing plant growth and development and is also a fundamental component of proteins [8]. Because soybean is capable of obtaining a substantial amount of nitrogen (N) through biological nitrogen fixation, its nitrogen fertilizer requirements are generally lower compared with many other crops. However, under severe drought conditions or when soil nutrient availability is extremely low, foliar fertilization [9] with nitrogen [10], phosphorus (P), potassium (K), and micronutrients may represent an alternative strategy for supplying plants with essential macro- and micronutrients.

Van Roekel et al. (2015) [11] emphasized that achieving maximum soybean yields requires not only the selection of suitable biological material but also the correct implementation of specific technological practices, including mineral fertilization with essential nutrients. Micronutrient deficiency has become an important limiting factor for crop productivity in agricultural regions worldwide [12]. Micronutrients play a critical role in plant physiology and, together with the main nutritional elements, contribute significantly to yield formation and seed quality [13].

The scientific literature supports the statement that biostimulants derived from seaweed extracts and seaweed-based products consistently improve soybean seed yield under different soil conditions, environments and application strategies [14]. Unlike synthetic chemicals, algae-based biofertilizers are environmentally friendly, non-toxic, non-polluting, and harmless to plants [15]. *Ascophyllum nodosum* (L.) Le Jolis belongs to the Phaeophyta group (brown algae) and is one of the most extensively studied marine algae species [16]. Extracts obtained from *Ascophyllum nodosum* have the potential to improve plant growth, yield, and quality because they contain plant growth regulators such as auxins, cytokinins, gibberellins, betaines, mannitol, organic acids, polysaccharides, amino acids, and proteins [17]. Therefore, biostimulants based on *Ascophyllum nodosum* are considered capable of improving productivity, increasing tolerance to biotic and abiotic stresses [18], and enhancing the physiological performance of soybean plants subjected to water-deficit conditions [19]. Recent studies have shown that the efficiency of foliar fertilization in soybean is strongly influenced not only by environmental conditions but also by genotype-specific responses and application timing. Different soybean cultivars may vary considerably in their capacity to absorb and utilize foliar-applied nutrients, leading to significant differences in grain yield and seed quality traits [20,21].

Although the beneficial effects of amino acid-based fertilizers and *Ascophyllum nodosum* extracts have been reported separately, limited information is available regarding their combined foliar application at different phenological stages and the extent to which soybean genotypes with contrasting maturity groups respond to these treatments. Therefore, the novelty of the present study lies in evaluating a combined amino acid–seaweed extract foliar fertilizer applied either at the V6 vegetative stage or the R1 reproductive stage across 30 soybean genotypes belonging to three maturity groups. This approach allows for the identification of the growth stage at which foliar fertilization is most effective for improving grain yield, protein content and oil content, while also assessing the role of genotype and environmental conditions in determining the response.

2. Materials and Methods

2.1. Research Area

The experiment was conducted at the Agricultural Development Research Station Turda (ARDS Turda), where the effects of mineral and foliar fertilization on soybean crops were evaluated under field conditions.

The ARDS Turda is situated within the Transylvanian Plateau, in the north-western part of the Turda municipality, at the geographical coordinates of 46°35' N latitude and 23°47' E longitude, and at an altitude ranging between 345 and 493 m above sea level. The region is characterized by favorable agroecological conditions for soybean cultivation, with moderate continental climatic influences specific to central Romania. Similar pedoclimatic conditions in the Transylvanian Plateau have previously been described as suitable for soybean production and varietal testing [22].

The experimental field was located on vertic Chernozem soil, characterized by a humus content of approximately 3.5%, low nitrogen and phosphorus availability, good potassium supply, and a neutral soil reaction. Chernozem soils are recognized for their relatively high natural fertility and favorable physical properties for soybean cultivation; however, nutrient limitations, particularly nitrogen and phosphorus, may influence crop productivity and seed quality under intensive agricultural systems.

2.2. Biological Materials

The biological material used in the experiment consisted of 30 soybean varieties belonging to three maturity groups (MGs): very early (MG 000), early (MG 00), and semi-early (MG 0) (Table 1). The studied germplasm included both foreign cultivars and soybean varieties developed at the Agricultural Development Research Station Turda (ARDS Turda), which is one of the main soybean breeding centers in Romania for early maturity groups [23] (www.eursoybreednet.com, accessed on 28 May 2026).

Table 1. The genotypes tested in the experiment.

No.	Genotypes	No.	Genotypes
1.	PERLA	16.	ILINCA TD
2.	CARLA TD	17.	BIA TD
3.	SULTANA	18.	TEO TD
4.	AMANDINE	19.	MIRUNA TD
5.	MERLINE	20.	NICOLA TD
6.	LISSABON	21.	LARISA
7.	GALLEC	22.	ADA TD
8.	ISA TD	23.	FELICIA TD
9.	IRIS TD	24.	RALUCA TD
10.	ZIANA TD	25.	BAHIA
11.	EUGEN	26.	TERRA PRO
12.	ONIX	27.	AIRES
13.	FELIX	28.	HILARIO
14.	CRISTINA TD	29.	LUCIJA
15.	CARO TD	30.	DACIANA

TD = Turda.

The first ten genotypes belonged to the very early maturity group (MG 000), genotypes 11–20 were classified within the early maturity group (MG 00), and the remaining ten genotypes belonged to the semi-early maturity group (MG 0). The selection of biological material was based on differences in genetic background, maturity groups, and adaptability to the pedoclimatic conditions of the Transylvanian Plain.

Several of the soybean cultivars included in the present study, such as Carla TD, Larisa, Felix, Ada TD, Felicia TD, Caro TD, Bia TD, Teo TD, Miruna TD, and Nicola TD, were developed within the soybean breeding program at ARDS Turda, which focuses on creating high-yielding cultivars with improved adaptability, seed quality, and suitability for mechanized harvesting [24–26].

2.3. Research Method

The experiment was conducted using a randomized complete block design (RCBD) with three replications for each treatment. Three fertilization treatments were evaluated, differing according to the timing of foliar fertilizer application during soybean developmental stages:

(I) Basic mineral fertilization (BMF) was applied before sowing and was considered the control treatment;

(II) Basic mineral fertilization (BMF) supplemented with foliar fertilization was applied at the V6 vegetative phenological stage (six fully developed trifoliate leaves) according to the scale proposed by Fehr and Caviness (1977) [27];

(III) Basic mineral fertilization (BMF) supplemented with foliar fertilization was applied at the R1 reproductive phenological stage (beginning flowering), according to Fehr and Caviness (1977) [27].

Each soybean genotype was sown in two rows, each 12 m in length, with 50 cm spacing between rows, resulting in a harvested plot area of 10 m². Sowing was carried out mechanically during the second decade of April using a Wintersteiger experimental plot seeder (Wintersteiger AG, Ried im Innkreis, Austria), at a density of 60 seeds m⁻².

The experimental field followed a three-year crop rotation system consisting of maize–winter wheat–soybean. Soil preparation included summer plowing followed by land leveling with a disk harrow in autumn. Prior to sowing, chemical weed control was performed using a combination of Sencor (Bayer CropScience, Monheim am Rhein, Germany) (0.35 kg ha⁻¹) and Spectrum (BASF, Ludwigshafen, Germany) (1.2 L ha⁻¹) herbicides, incorporated into the soil during seedbed preparation with a combinator. Weed management during the growing season consisted of two mechanical hoeings, supplemented by manual hoeing when necessary. No additional phytosanitary treatments against diseases or pests were required throughout the experimental period.

Mineral fertilization was performed before sowing using granulated nitrocalcium fertilizer applied at a rate of 100 kg ha⁻¹, containing 27% total nitrogen, including 13.5% nitric and ammoniacal nitrogen, as well as secondary nutrients and microelements, such as 7% CaO and 5% MgO.

The foliar fertilizers evaluated in the experiment were commercial products manufactured by Daymsa (Paterna, Valencia, Spain) [28] and were applied according to the manufacturer's recommendations. The foliar fertilization scheme included Naturamin WSP, a water-soluble microgranular fertilizer containing 80% (w/w) free amino acids, 12.8% total nitrogen, and 12.8% organic nitrogen, applied at a rate of 0.5 kg ha⁻¹. In addition, Pleniflor and Naturfruit liquid foliar fertilizers were applied at a rate of 2 L ha⁻¹; these products contain high potassium concentrations (25% K₂O w/w; 38% K₂O w/v), water-soluble boron (9% w/w), water-soluble molybdenum (1% w/w) and extracts from the seaweed *Ascophyllum nodosum*. Based on the applied doses and product composition, Naturamin WSP supplied approximately 64 g N ha⁻¹, while Pleniflor and Naturfruit supplied approximately 760 g K₂O ha⁻¹, together with boron and molybdenum, according to the manufacturer's specifications.

Phenological observations, including emergence, beginning of flowering, and physiological maturity, were recorded according to the soybean developmental scale described

by Fehr and Caviness (1977) [27]. Foliar fertilization treatments were applied manually using a backpack sprayer when each genotype reached the V6 vegetative stage and the R1 reproductive stage.

At the end of the growing season, all experimental plots were mechanically harvested and the seed yield was recorded, adjusted to standard moisture content and expressed per hectare. Harvesting was carried out mechanically during September–October using a Wintersteiger experimental plot combine harvester (Wintersteiger AG, Ried im Innkreis, Austria). A 300 g seed sample was taken from each variant and analyzed for protein and oil contents using near-infrared (NIR) spectroscopy. Chemical composition was determined non-destructively using an FT-NIR Tango spectrophotometer (Bruker Optik GmbH, Ettlingen, Germany).

2.4. Climatic Condition of the Experimental Years

Meteorological data were obtained from the Turda Meteorological Station, located in close proximity to the experimental field, and the recorded data accurately represent the environmental conditions experienced by the soybean crop during both growing seasons and are consistent with the climatic characteristics of the Transylvanian Plateau reported in previous studies.

The experimental years showed considerable differences in climatic conditions during the soybean vegetation period (Figure 1) [29]. Regarding air temperature, a slight increase was observed in 2020 compared to 2021 during the early stages of crop development, from emergence (last decade of April–May). During the summer months (June, July, and August), temperature dynamics varied between the two years; however, in 2021 a decrease in temperature was recorded during the late vegetation period, corresponding to the beginning and end of seed maturity stages.

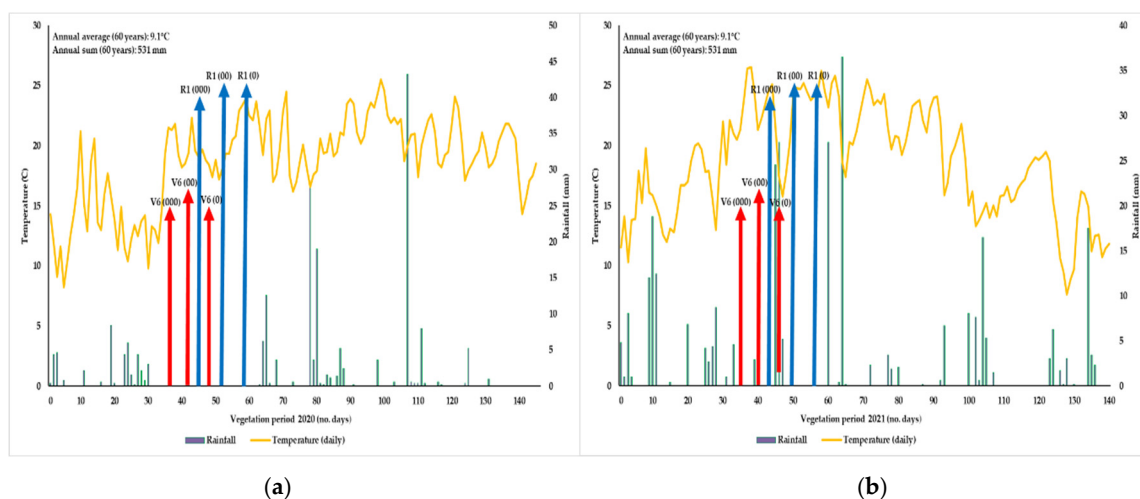


Figure 1. (a) The climatic conditions of the first season (2020); (b) the climatic conditions of the second season (2021). (000), (00) and (0) represent the time when the three maturity groups reached the V6 and R1 stages, respectively (Source of primary data: Turda Meteorological Station—longitude: 23°47′; latitude: 46°35′; altitude: 427 m).

Regarding precipitation, a clear contrast was observed between the two experimental years. As shown in Figure 1, the year 2020 was considerably drier throughout the soybean growing season compared to 2021. Accordingly, 2020 can be characterized as a warmer and drier climatic year, whereas 2021 exhibited higher precipitation levels and a more balanced thermal regime for the reference area. Similar observations were reported in studies emphasizing that soybean productivity and seed quality are strongly influenced

by climatic variability, especially temperature and water availability during reproductive stages [30–32].

From the perspective of fertilizer application timing, 2020 was characterized by a lack of rainfall during foliar fertilization events, whereas in 2021 foliar applications were performed after rainfall periods, with subsequent rainy days occurring after treatment application. The contrasting climatic conditions between the two experimental years were considered an important source of environmental variability. Therefore, treatment effects were interpreted across both years, taking into account that precipitation and temperature during the growing season might interact with foliar nutrient uptake and soybean physiological responses. Previous studies demonstrated that adequate moisture availability following foliar nutrient application may enhance nutrient uptake efficiency, improve physiological activity, and contribute to increased seed yield and quality parameters [30,31].

2.5. Statistical Data

The experimental data were subjected to statistical analysis using the Poly Fact Program Software 2020. Data were analyzed using a three-way analysis of variance (ANOVA), considering year (Y), maturity group (MG), and fertilization treatment (T) as factors, to evaluate the effects of foliar fertilization treatments, phenological stages, and soybean maturity groups on grain yield and quality parameters. Mean comparisons were conducted using Fisher's protected Least Significant Difference (LSD) test at the 5% probability level ($p \leq 0.05$). Fisher's protected LSD was selected because the experiment had a balanced factorial design with a limited number of treatment levels and mean comparisons were performed to highlight treatment differences.

The graphical representation of the experimental results, including yield and quality parameter dynamics, was performed using Microsoft Excel.

Furthermore, Linear Discriminant Analysis (LDA) was carried out using Past4 software to assess the multivariate differentiation among soybean maturity groups and fertilization treatments based on the investigated agronomic and quality traits. The LDA ordination plots enabled the visualization of treatment clustering patterns and the identification of the variables contributing most strongly to group separation. Principal component analysis (PCA) was conducted using PAST 5 software based on the correlation matrix to evaluate the relationships among soybean seed yield, protein content, and oil content under the different fertilization treatments.

3. Results

The results of the ANOVA (Table 2) showed that the experimental year had a highly significant effect on seed yield and oil content, while its influence on protein content was only weakly significant. Higher seed yield (2817 kg ha^{-1}) and oil content (23.17%) were recorded in 2020 compared with 2021 (2550 kg ha^{-1} and 22.09%, respectively), whereas protein content remained relatively stable between years. The maturity group significantly affected all studied traits, with the strongest effects observed for protein and oil content. Among the maturity groups, MG 0 showed the highest seed yield (2821 kg ha^{-1}), as well as the highest oil content, while MG 00 recorded the lowest values. Fertilization treatment did not significantly influence seed yield (ns) but had a significant effect on protein and oil content. Treatment T2 resulted in the highest oil content (22.68%), whereas T1 was associated with a reduction in protein content (36.12%). Overall, the results indicate that year conditions and maturity group exerted a stronger influence on soybean yield and quality than fertilization treatments, particularly for seed yield and oil accumulation.

The Linear Discriminant Analysis (LDA) (Figure 2) revealed a clear separation between the soybean maturity groups and foliar fertilization treatments at different phenological

stages across the two experimental years. Axis 1 explained 89.91% of the total variability, while Axis 2 explained 7.79%, indicating that most of the variation among treatments and maturity groups was concentrated on the first principal component. The treatments applied during Season 1 and Season 2 formed separate clusters, indicating that the response of soybean varieties is influenced by environmental conditions and foliar fertilization. The separation of treatments between the two growing seasons observed in the LDA ordination indicates that environmental conditions substantially contributed to the overall variability, and the effect of fertilization in the differentiation of experimental variants is evident. The response pattern differed among maturity groups. Early maturity cultivars exhibited moderate yield increases, while cultivars from later maturity groups generally showed higher yield. Foliar applications performed during the vegetative stage (V6) tended to produce more pronounced increases in yield compared with treatments applied at the reproductive stage (R1).

Table 2. ANOVA for the effects of year, maturity group and fertilization on soybean yield, protein content and oil content.

Factor		Yield	Protein	Oil
Year (Y)	Average	2684 ^{Ct}	37.54 ^{Ct}	22.63 ^{Ct}
	2020	2817 [*]	37.38 ^{ns}	23.17 ^{***}
	2021	2550 ⁰	37.69 ^{ns}	22.09 ⁰⁰⁰
Maturity group (MG)	MG 000	2659 ^{ns}	38.28 ^{***}	22.60 ^{ns}
	MG 00	2571 ^{Ct}	36.83 ^{Ct}	22.58 ^{Ct}
	MG 0	2821 ^{**}	37.50 ^{***}	22.71 ^{***}
Treatment (T)	Ct.	2635 ^{Ct}	38.36 ^{Ct}	22.60 ^{Ct}
	T1	2726 ^{ns}	36.12 ⁰⁰⁰	22.60 ^{ns}
	T2	2690 ^{ns}	38.14 ⁰⁰⁰	22.68 ^{***}
ANOVA	Y	***	*	***
	MG	**	***	***
	T	ns	***	**

***, 000: significant at 0.001 (positive and negative); **, significant at 0.01 (positive and negative); *, 0: significant at 0.05 (positive and negative); ns: not significant; Ct—basic mineral fertilization (BMF); T1—basic mineral fertilization (BMF) + foliar application at the V6 vegetative phenological stage; T2—basic mineral fertilization (BMF) + foliar application at the R1 reproductive phenological stage.

The grain yield results showed differences among soybean maturity groups and foliar fertilization treatments (Figure 3). For MG 000, grain yield ranged from 2533 to 2665 kg ha^{−1}. The foliar application performed at the V6 vegetative stage resulted in the highest yield (2665 kg ha^{−1}), compared with the basic mineral fertilization treatment (2573 kg ha^{−1}) and the foliar application at the R1 reproductive stage (2533 kg ha^{−1}).

In MG 00, the same trend was observed. The V6 foliar application produced the highest grain yield (2663 kg ha^{−1}), followed by the R1 application (2539 kg ha^{−1}) and the control treatment with only basic mineral fertilization (2510 kg ha^{−1}).

The highest grain yields were recorded in MG 0, with values ranging from 2801 to 2845 kg ha^{−1}. In this group, the R1 foliar treatment showed the greatest numerical yield (2845 kg ha^{−1}), although the differences among treatments appeared smaller compared with those in earlier maturity groups.

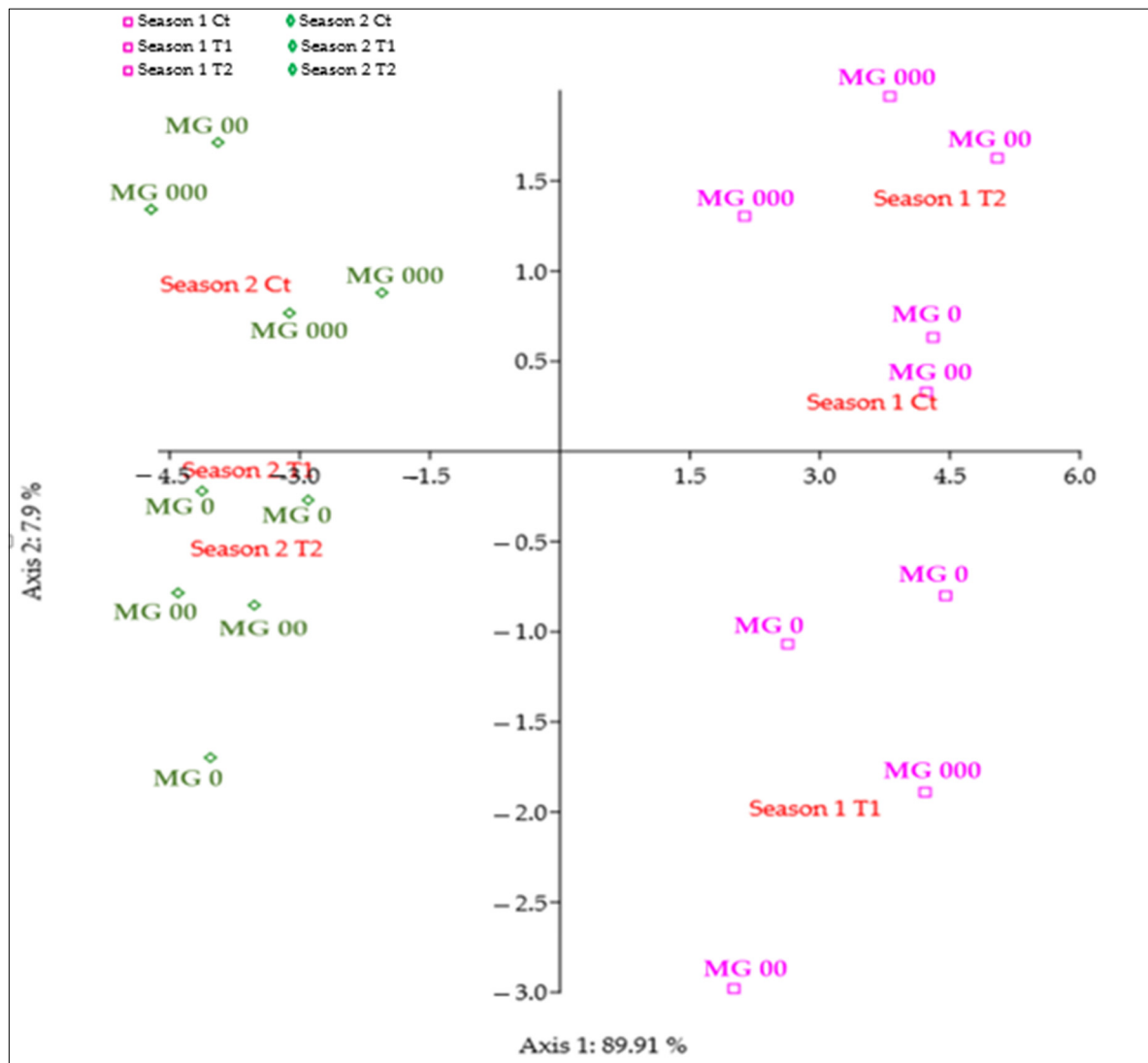


Figure 2. Linear Discriminant Analysis (LDA) between the first (2020) and second (2021) growing seasons. MG—maturity group; Ct—basic mineral fertilization (BMF); T1—basic mineral fertilization (BMF) + foliar application at the V6 vegetative phenological stage; T2—basic mineral fertilization (BMF) + foliar application at the R1 reproductive phenological stage.

Significant differences were revealed among maturity groups and treatments. In general, soybean cultivars from MG 0 achieved superior grain yield compared with MG 00 and MG 000 cultivars, indicating that foliar fertilization, particularly when applied at the V6 stage, may positively influence soybean productivity, although the magnitude of the response depended on maturity group and environmental conditions.

Figure 4 illustrates the percentage increase in soybean grain yield in response to foliar fertilization treatments across different maturity groups and cultivars. The response varied considerably depending on genotype and application timing, indicating distinct physiological reactions among soybean cultivars. The highest increases in yield reached up to 18%; furthermore, more than 50% of the soybean cultivars showed a positive response to foliar fertilization applied at the V6 phenological stage, with yield increases varying between 1% and 18%. The response pattern differed among maturity groups. Early maturity cultivars exhibited moderate yield increases, while cultivars from later maturity groups generally showed greater yield stability and, in several cases, higher relative productivity gains. Several varieties showed only limited improvements or inconsistent

responses, suggesting that the efficiency of foliar fertilization is strongly influenced by genotype $\times$ environment interactions and the physiological capacity of each cultivar to utilize supplemental nutrients.

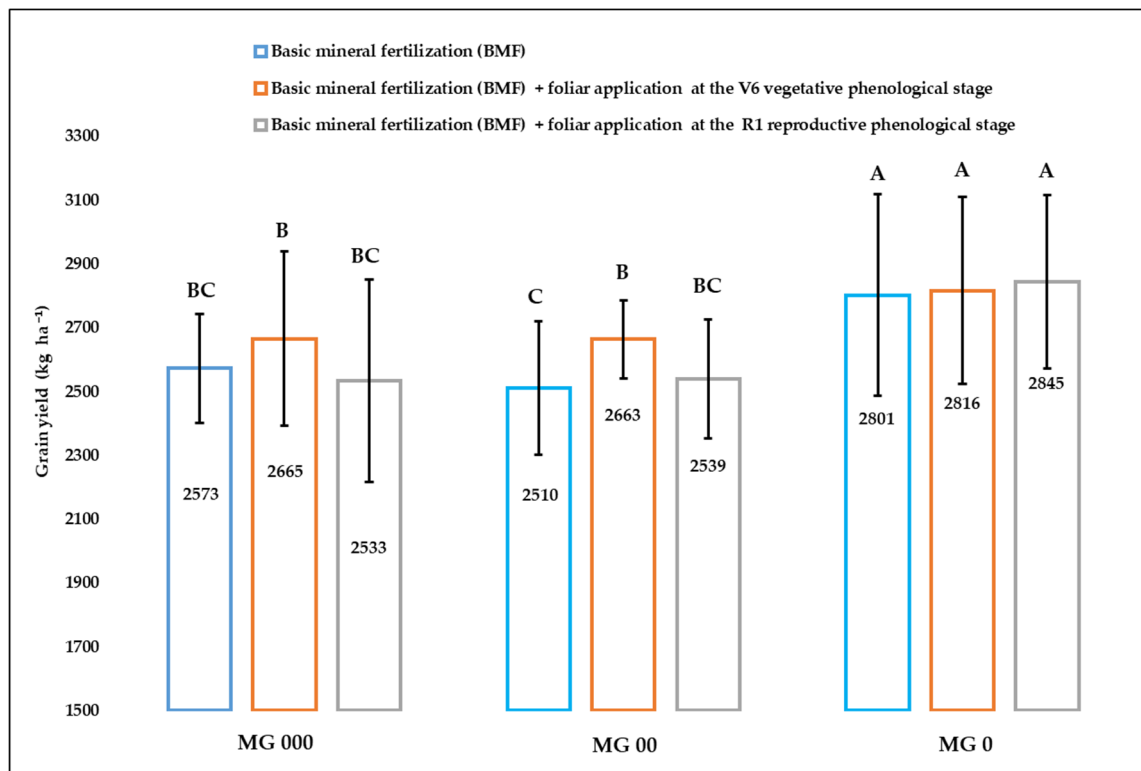


Figure 3. Soybean grain yield response to foliar fertilization treatments at different phenological stages. Means followed by different letters are significantly different according to Fisher's protected LSD test at $p \leq 0.05$.

Soybean protein content was influenced differently by foliar fertilization depending on the maturity group and the phenological stage of application (Figure 5). In the very early soybean group, the highest protein content was recorded under basic mineral fertilization (39.33%), followed closely by foliar application at the R1 reproductive stage (39.23%), while foliar fertilization applied at the V6 vegetative stage resulted in a significant decrease in protein content (36.66%). A similar trend was observed in the early maturity group, where foliar application at V6 led to the lowest protein content (34.43%) compared with basic mineral fertilization (38.45%) and foliar application at R1 (37.61%). In the semi-early group, differences among treatments were minimal, with protein content values ranging between 37.38% and 37.69%, suggesting a limited effect of foliar fertilization.

Foliar application at the V6 vegetative stage had little to no positive effect on protein accumulation (Figure 6), with most varieties showing no increase compared with the basic mineral fertilization treatment. Only a few cultivars from the MG 0 group, such as Terra PRO, Aires, Hilario, and Daciana, recorded slight increases ranging from 1% to 3%.

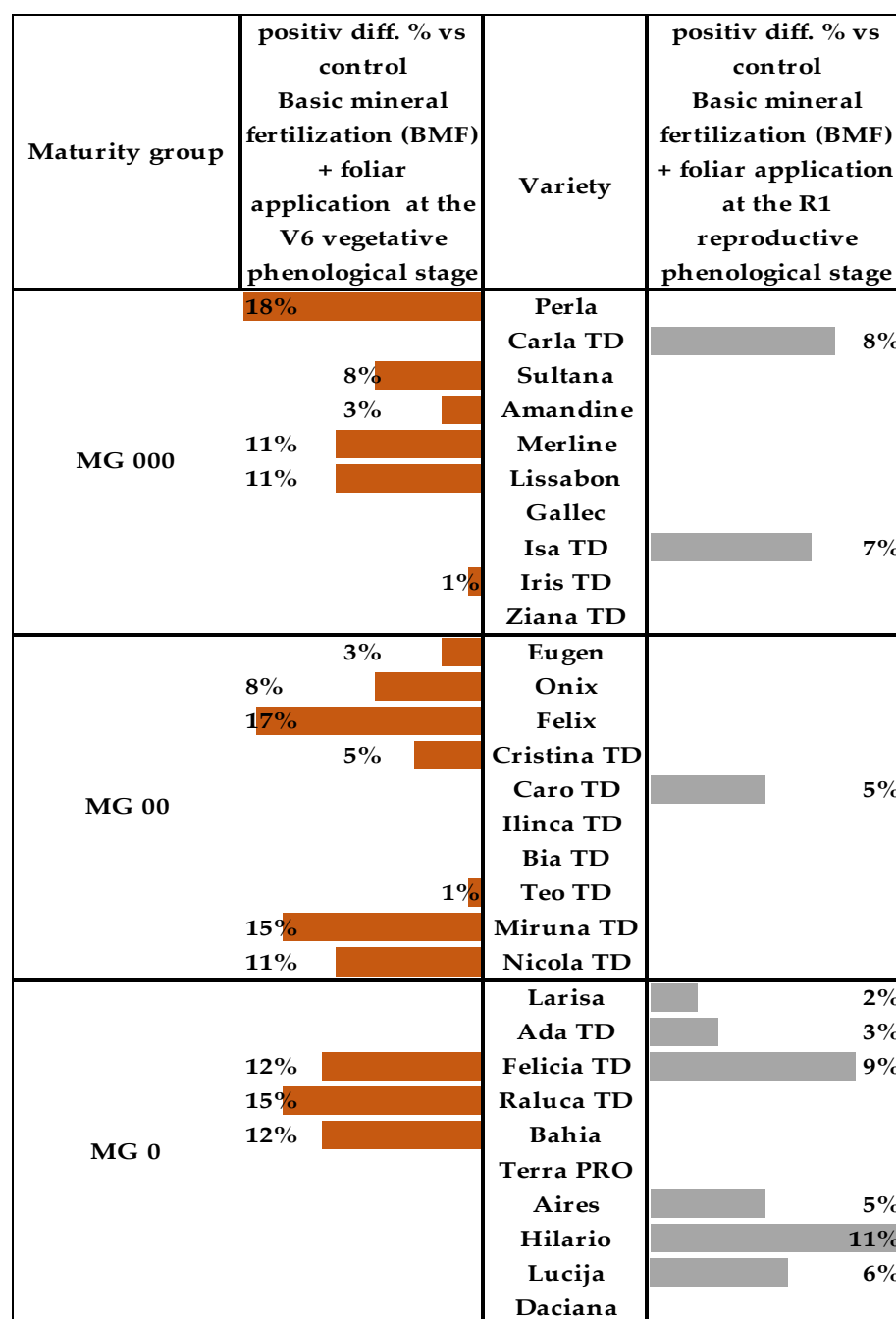


Figure 4. Percentage increase in soybean grain yield under different foliar fertilization treatments across maturity groups and varieties. MG—maturity group.

In contrast, foliar fertilization applied at the R1 reproductive stage resulted in a more pronounced enhancement of protein content across most soybean varieties. Within MG 000, protein increases ranged from 4% to 10%, with the highest response observed in the cultivar Isa TD (10%), followed by Iris TD (9%) and Ziana TD (8%). In MG 00, the response was even stronger, with several cultivars showing increases between 6% and 11%. The greatest improvements were recorded for Ilinca TD and Teo TD, both with an 11% increase in protein content. MG 0 exhibited a comparatively weaker response to foliar fertilization at R1, with increases generally ranging from 0% to 4%. Some cultivars, including Ada TD, Felicia TD, and Raluca TD, showed no improvement, indicating genotype-dependent variability in protein accumulation. Overall, the results suggest that foliar fertilization applied during the R1 reproductive stage is more effective at stimulating soybean protein

synthesis than application at the V6 vegetative stage, particularly in early and semi-early maturity groups.

Soybean oil content (Figure 7) showed only slight variations among fertilization treatments and maturity groups, indicating a relatively limited response to foliar fertilization. In MG 000, the highest oil content values were recorded under foliar fertilization applied at both the V6 and R1 stages (22.71%), compared with the basic mineral fertilization treatment (22.40%). In MG 00, the highest oil content was observed following foliar application at the R1 reproductive stage (22.62%), while the lowest value was recorded for foliar application at V6 (22.52%). For MG 0, the greatest oil content was obtained under basic mineral fertilization (22.81%), whereas foliar fertilization at V6 slightly reduced oil accumulation (22.59%). Overall, the differences among treatments were small, suggesting that foliar fertilization timing had a minor influence on soybean oil content.

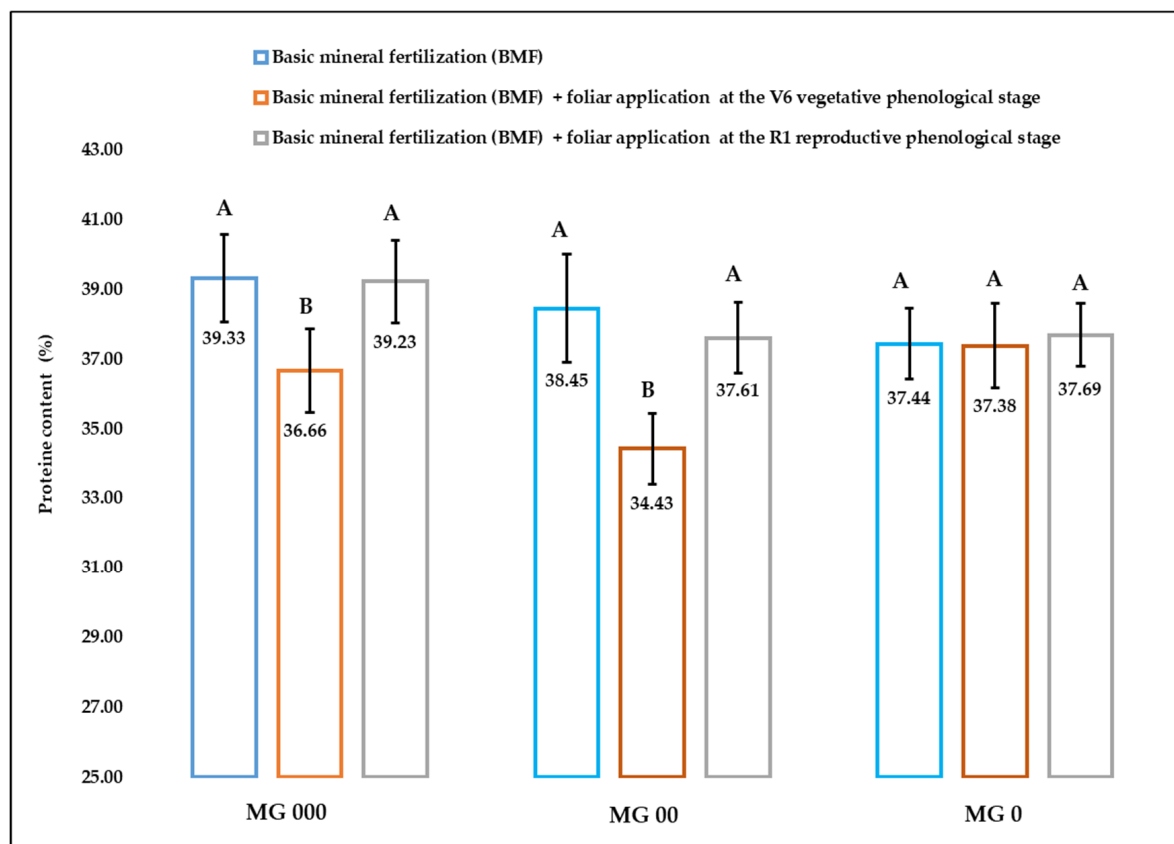


Figure 5. Soybean protein content response to foliar fertilization treatments at different phenological stages. Means followed by different letters are significantly different according to Fisher's protected LSD test at $p \leq 0.05$.

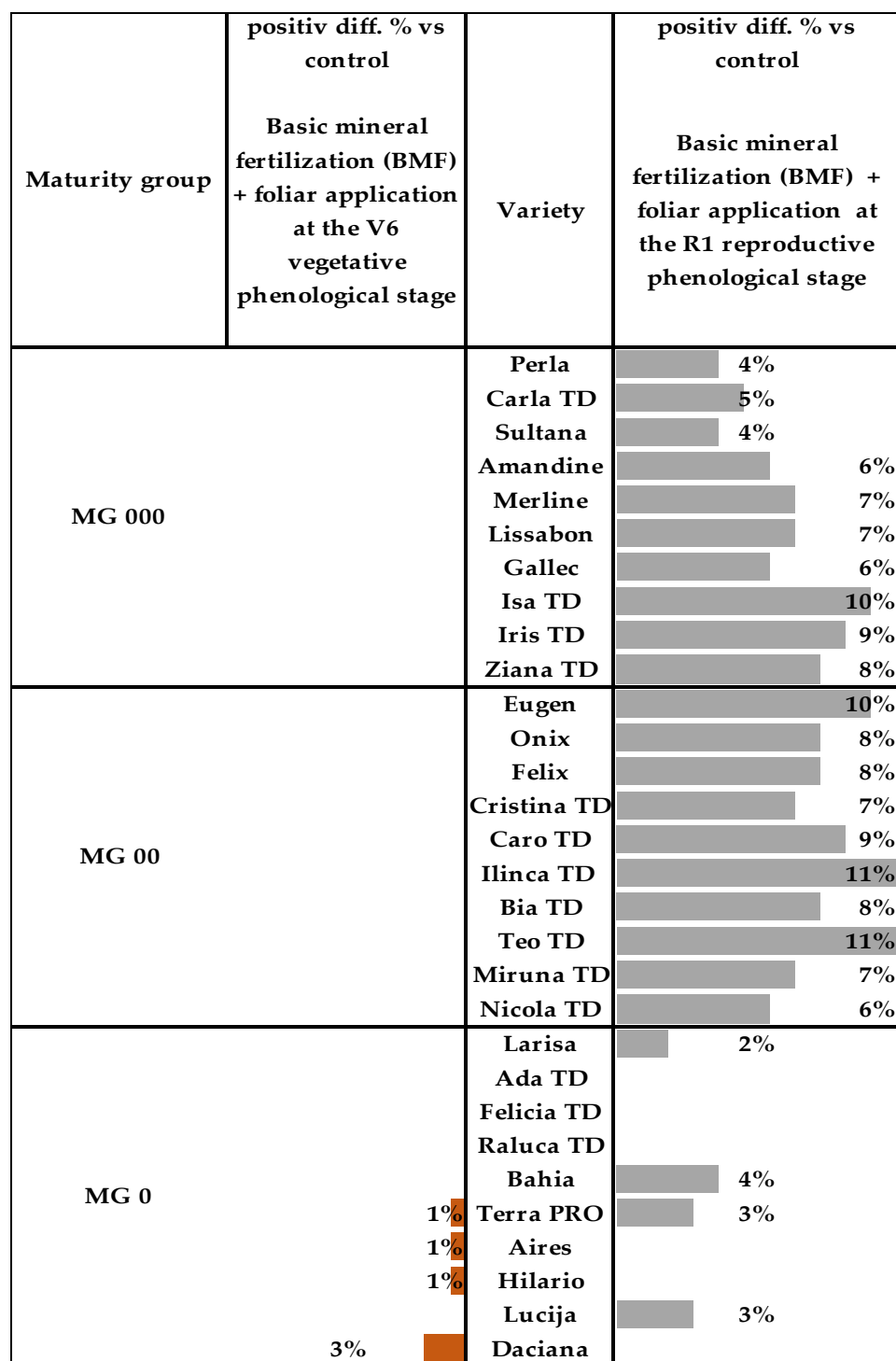


Figure 6. Percentage increases in soybean protein content under different foliar fertilization treatments across maturity groups and varieties.

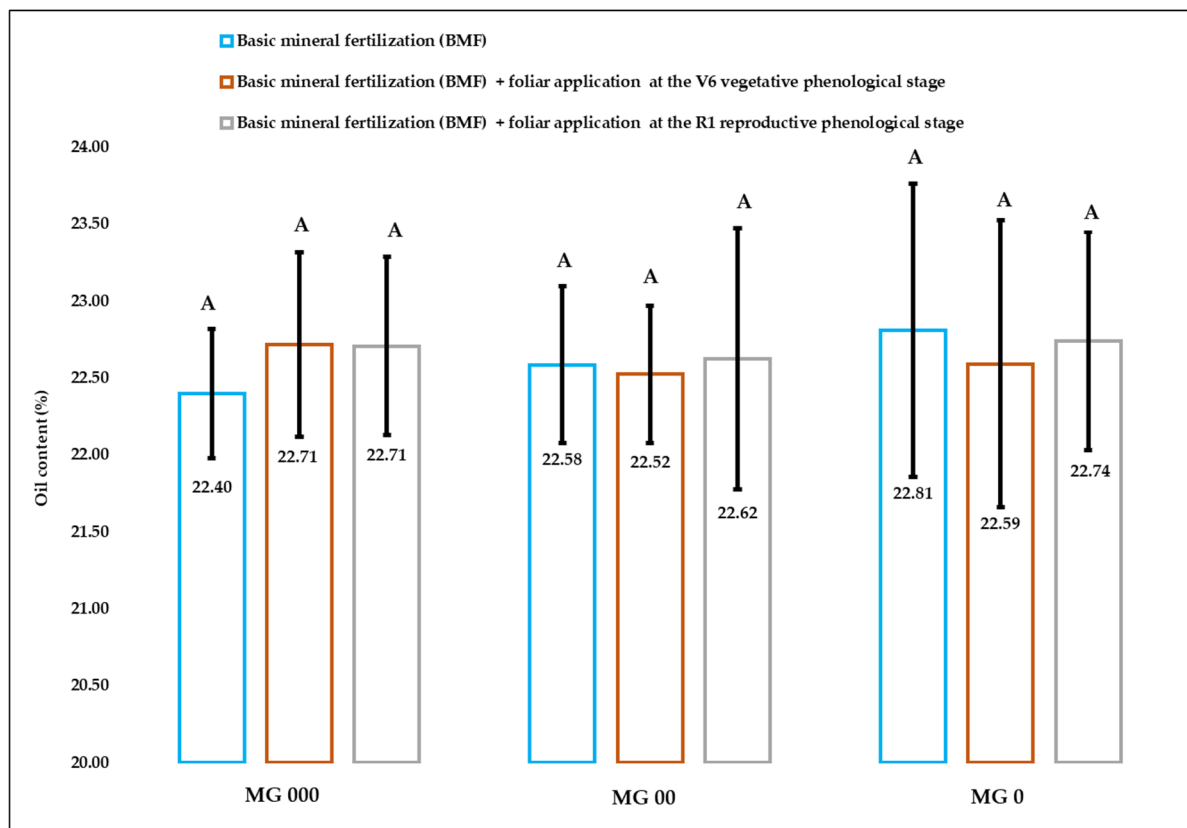


Figure 7. Soybean oil content response to foliar fertilization treatments at different phenological stages. Means followed by different letters are significantly different according to Fisher's protected LSD test at $p \leq 0.05$.

Compared with protein content, the response of oil accumulation to foliar fertilization was generally lower and more variable among cultivars (Figure 8). Foliar fertilization applied at the V6 vegetative stage produced moderate increases in oil content, ranging from 1% to 4%. The highest increases were observed in Carla TD and Lissabon (4%), while several varieties, such as Merline and Iris TD, showed no response. Under the R1 reproductive stage treatment, most cultivars exhibited limited or no increases in oil content, with only Ziana TD reaching a 4% improvement. Within MG 00, the overall response remained relatively small. Some cultivars, including Miruna TD and Nicola TD, recorded increases of 2% and 4%, respectively, under foliar fertilization at the R1 stage, while other varieties showed either marginal or no changes. Foliar application at V6 generated only slight improvements, generally between 0% and 2%. MG 0 displayed the weakest response in terms of oil accumulation. Most cultivars showed no increase regardless of treatment, although Bahia presented a 3% increase under V6 application, while Raluca TD and Daciana each recorded a 3% increase under R1 application.

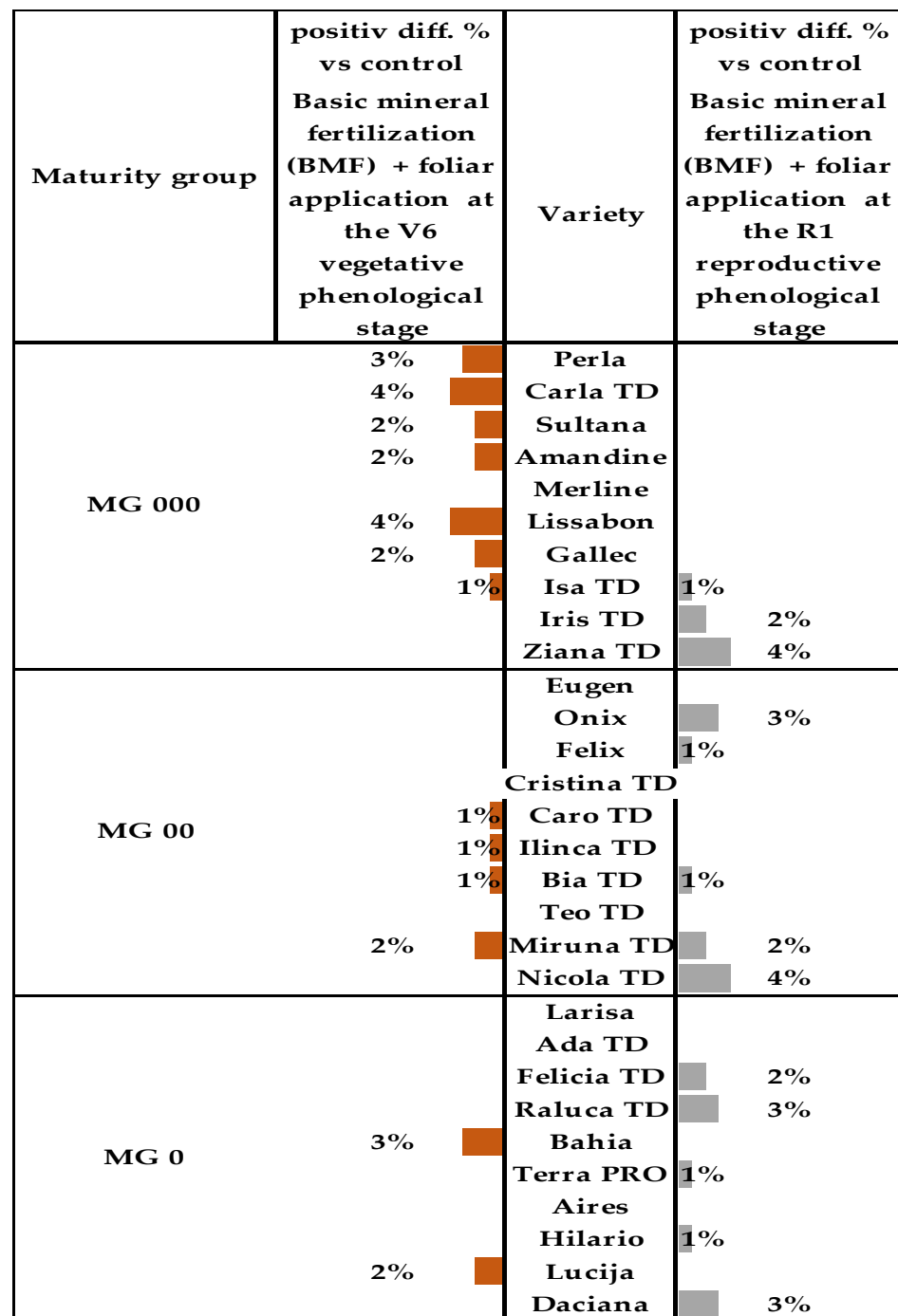


Figure 8. Percentage increases in soybean oil content under different foliar fertilization treatments across maturity groups and varieties.

The principal component analysis (PCA) revealed distinct responses of soybean yield and quality traits to the fertilization treatments (Figure 9). Higher protein content was associated with the control treatment, while the highest seed yield and oil content were recorded under the first foliar fertilization treatment, which consisted of basic mineral fertilization (BMF) supplemented with foliar fertilization applied at the V6 vegetative phenological stage. The loading plot indicated that seed yield and oil content were strongly and positively associated along PC1, suggesting that these traits responded similarly to the fertilization treatments. Conversely, protein content exhibited a weak negative association with PC1 and a weak negative correlation with both seed yield and oil content, indicating

an inverse but less pronounced relationship between protein concentration and the other evaluated traits.

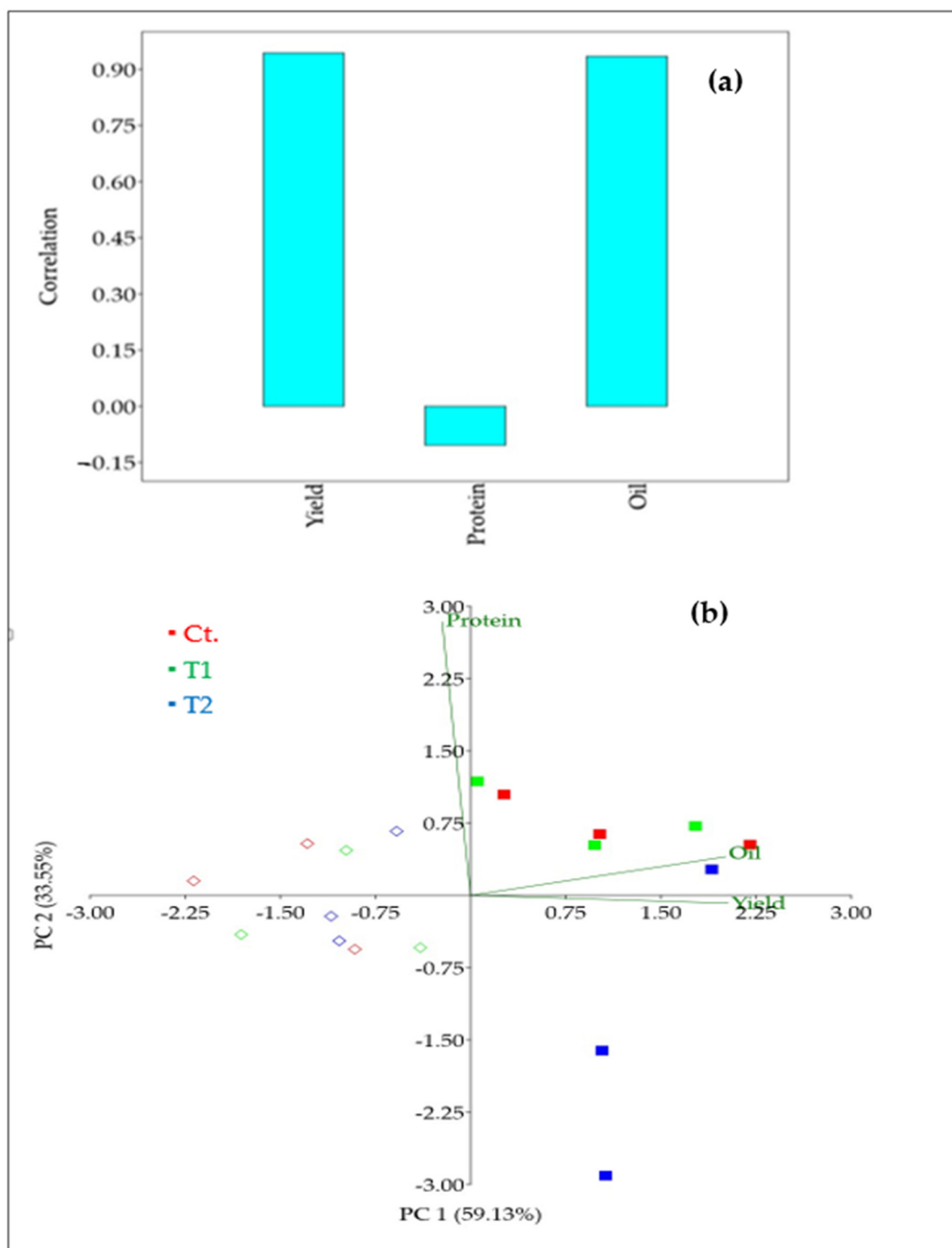


Figure 9. Principal component analysis (PCA) loadings (a) and biplot (b) for soybean yield and quality traits. Ct—basic mineral fertilization (BMF); T1—basic mineral fertilization (BMF) + foliar application at the V6 vegetative phenological stage; T2—basic mineral fertilization (BMF) + foliar application at the R1 reproductive phenological stage (■ Season 1; ◇ Season 2).

4. Discussion

Given the growing use of macro- and micronutrients combined with seaweed extracts as a complementary foliar fertilization strategy, the present study was designed to assess the agronomic effectiveness of different application timings by evaluating their effects on crop productivity and quality characteristics. In the present study, foliar application at the V6 vegetative stage consistently resulted in higher grain yield than application at the R1 reproductive stage, indicating that the timing of nutrient supply is a critical factor determining soybean response. The greater effectiveness of the V6 treatment is likely associated with enhanced canopy development and photosynthetic activity during the vegetative phase, when nutrient availability directly influences leaf expansion and biomass accumulation. Similar findings were reported by [33–35], who observed improvements in plant metabolism resulting directly in enhanced yield components and grain production. The results obtained in the present study indicate that the timing of foliar fertilization is extremely important, with the highest grain yields achieved when fertilization was applied at the V6 stage. Foliar application allows plants to rapidly absorb nutrients, particularly under drought conditions [36]. Therefore, the higher yields observed in the present study are likely the result of improved plant nutritional status during a period of active vegetative growth rather than the direct effect of foliar fertilization. The different climatic conditions recorded during the two experimental seasons likely influenced the magnitude of soybean responses to foliar fertilization. The drier conditions in 2020 may have limited nutrient absorption and translocation following foliar application, whereas the higher precipitation recorded in 2021 probably enhanced nutrient uptake and physiological activity. The beneficial effects of foliar fertilization cannot be interpreted independently of environmental conditions, supporting the importance of year $\times$ treatment $\times$ genotype interactions in soybean production.

Although the positive effects of foliar fertilization on soybean productivity have been highlighted by studies conducted under different environmental conditions, with researchers reporting yield increases ranging from 3.16% [37] to 27.0% [38] following the application of fertilizers containing extracts of *Ascophyllum nodosum*—values similar to those obtained in the present study—foliar fertilization cannot be considered a major factor determining yield formation. The largest differences were associated with the year effect, where climatic conditions had a strong influence on soybean productivity.

The response also differed among maturity groups. Cultivars belonging to MG 0 consistently produced higher grain yields than MG 000 cultivars, reflecting the longer growing period available for biomass accumulation and reproductive development. Cultivars with a longer vegetation period generally achieved higher productivity than very early cultivars because they had more time for growth, development of assimilation organs, and yield formation, as also reported by [32]. The biological material belonging to the three maturity groups reacted differently to foliar fertilization at both vegetation stages (V6 and R1), demonstrating that maturity group is an important factor influencing soybean productivity. The results of the present study showed that cultivars from MG 0 produced higher yields than cultivars from MG 000. These findings are in contrast with those reported by [39,40], who hypothesized that late-maturing cultivars exhibit lower productivity than early maturing cultivars. Under the environmental conditions of the Transylvanian Plateau, the longer vegetation period of MG 0 cultivars appears to provide sufficient time for assimilate accumulation without exposing plants to excessive late-season stress, thereby contributing to higher grain yield.

While foliar fertilization at the V6 stage maximized grain yield, the greatest increases in seed protein content were obtained when nutrients were applied at the R1 reproductive stage. This response is physiologically consistent with soybean nitrogen metabolism.

During flowering and early pod development, nitrogen remobilization from vegetative tissues toward developing seeds becomes increasingly important, and the additional nutrient supply may therefore support protein synthesis more efficiently than earlier applications. The stronger response observed in MG 000 and MG 00 cultivars also suggests that early maturing genotypes may be more responsive to supplemental nutrients during reproductive development because of their shorter seed-filling period. Although the highest grain yields were obtained when foliar fertilization was applied at the V6 stage, protein content was reduced under this treatment. Furthermore, protein concentration tended to be negatively correlated with seed yield, indicating that higher-yielding treatments generally showed lower protein accumulation. In contrast, oil concentration appeared to be positively associated with grain yield, with higher-yielding treatments generally accompanied by slightly increased oil accumulation, as reported by [41]. Significant increases in protein percentage were observed when foliar fertilization was applied at the R1 reproductive stage, especially in cultivars belonging to MG 000 and MG 00, while the response was less pronounced in MG 0 cultivars. However, the recorded differences were not always statistically significant.

Regarding seed composition variability, particularly protein concentration, this trait can be influenced by genotype, environment, crop management practices, and their interactions [42]. In the scientific literature, relatively few studies have investigated the combined effect of foliar fertilization applied at different soybean phenological stages, as was also noted by [43].

The results obtained in the present study, together with those reported by [44], indicate that soil mineral fertilization supplemented with foliar applications of macro- and micronutrients can improve nutrient use efficiency, stabilize grain yield, and contribute to improved soybean seed quality. These findings support the integration of foliar fertilization with conventional mineral fertilization as a complementary strategy for enhancing soybean productivity and seed quality under the variable climatic conditions characteristic of the Transylvanian Plateau. Foliar fertilization is suitable for cultivars exhibiting a consistently high agronomic response, while its adoption in low-responsive cultivars should be evaluated together with economic considerations.

5. Conclusions

Foliar fertilization influenced soybean grain yield and seed quality differently depending on maturity group, genotype, phenological stage of application, and climatic conditions. The application of foliar fertilizers at the V6 vegetative stage generally resulted in the highest grain yields, especially in MG 000 and MG 00, confirming the importance of nutrient availability during early vegetative development. Yield increases varied considerably among cultivars, reaching up to 18% in some genotypes, which demonstrates the strong influence of genotype $\times$ environment interactions on soybean response to foliar fertilization.

Regarding seed quality, foliar fertilization applied during the R1 reproductive stage proved more effective in increasing protein accumulation, particularly in cultivars from MG 000 and MG 00. In contrast, foliar fertilization at V6 frequently reduced protein concentration despite improving grain yield, confirming the negative relationship often observed between yield and protein content. Oil content was influenced only slightly by foliar fertilization, suggesting that soybean oil accumulation is more stable and less responsive to supplemental foliar nutrients.

The results indicate that foliar fertilization can represent a useful complementary practice for soybean cultivation, stabilizing yield, and partially enhancing seed quality. The results indicate that the response to foliar fertilization was strongly influenced by envi-

ronmental conditions, suggesting that its effectiveness may be limited under unfavorable climatic conditions. Further research should focus on the interaction between genotype, environmental conditions, and foliar nutrient formulations in order to optimize soybean fertilization strategies for different maturity groups and production environments.

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