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# THE IMPACT OF NITROGEN FERTILIZATION ON THE PRODUCTIVITY OF SOYBEAN CROPS IN SOUTHERN AND CENTRAL ROMANIA IN THE CONTEXT OF CLIMATE CHANGE

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***Abstract***

*This study investigates the effects of nitrogen fertilization on the productivity of soybean crops in Southern and Central Romania under changing climatic conditions. The research focuses on two soybean varieties, Amiata and Orakel, cultivated in the regions of Caracal and Crişcior, which differ in soil characteristics and environmental stressors. Field experiments were conducted using three nitrogen application rates, and key agronomic traits such as plant height, number of pods, grain yield, and seed quality parameters were measured. Although statistical analysis did not reveal significant differences across treatments, strong positive correlations between nitrogen levels and several performance indicators were observed. The findings underscore the importance of adaptive nitrogen management strategies for maintaining soybean productivity and resilience in climate-sensitive agricultural regions.*

***Key words***: *climate, nitrogen, productivity, soybean, sustainability*.

## INTRODUCTION

The global challenges posed by climate change have significantly impacted agricultural systems worldwide, compelling researchers and practitioners to seek innovative solutions to ensure food security and sustainability. Soybean (*Glycine max* L.) is a crop of paramount economic and nutritional importance, particularly in regions like Southern and Central Romania, where agricultural productivity is increasingly constrained by environmental variability. This study investigates the critical role of nitrogen fertilization in enhancing soybean productivity, focusing on the interplay between nitrogen application and climatic stressors such as drought, temperature fluctuations, and irregular precipitation patterns. Understanding these interactions is essential for developing resilient and adaptive agricultural practices tailored to climate-sensitive regions.

Nitrogen is a vital nutrient that profoundly influences plant growth and productivity (Zhang et al., 2021). In the context of soybean cultivation, nitrogen management is particularly complex due to the crop's ability to fix atmospheric nitrogen through symbiotic relationships with rhizobia. However, under stressful climatic conditions, the efficiency of biological nitrogen fixation may decline, necessitating the application of nitrogen fertilizers to maintain yield levels (López-Bellido et al., 2020). This dual reliance on biological and synthetic nitrogen sources underscores the need for precise management strategies that optimize nitrogen use while minimizing environmental impacts.

Recent studies highlight the exacerbating effects of climate change on nitrogen dynamics in agricultural soils. For instance, drought conditions can impair nitrogen availability and uptake, while excessive rainfall can lead to nitrogen leaching and loss (Schlesinger & Bernhardt, 2020). Such challenges are particularly pronounced in Romania, where climate projections indicate increased variability in precipitation and rising temperatures (Ion et al., 2021). These climatic shifts demand a reevaluation of fertilization practices to ensure both productivity and environmental sustainability.

Field-based research provides invaluable insights into the complex interactions between nitrogen application, crop physiology, and environmental factors. Experiments conducted in similar agro-climatic regions have

demonstrated that tailored nitrogen management can significantly enhance soybean yields, even under adverse conditions (Singh et al., 2021). For example, split application of nitrogen fertilizers has been shown to improve nitrogen use efficiency and reduce losses, thereby supporting sustainable production systems (Chen et al., 2020). Furthermore, integrating organic amendments such as compost or biochar with synthetic fertilizers can enhance soil health and mitigate the ecological footprint of fertilization practices (Gao et al., 2021).
The environmental implications of nitrogen fertilization extend beyond soil health to encompass broader ecological concerns. Excessive nitrogen application is a major contributor to greenhouse gas emissions, particularly nitrous oxide, a potent greenhouse gas (Davidson et al., 2021). Additionally, nitrogen runoff into water bodies can lead to eutrophication, disrupting aquatic ecosystems (Vitousek et al., 2021). These challenges necessitate the adoption of integrated nutrient management approaches that balance productivity goals with ecological stewardship.
In this context, the concept of sustainable intensification emerges as a guiding principle for modern agriculture. Sustainable intensification seeks to increase crop yields on existing farmland while minimizing negative environmental impacts (Pretty et al., 2020). For soybean cultivation, this approach involves leveraging advanced technologies such as precision agriculture to optimize nitrogen application rates and timings. Moreover, fostering farmer awareness and capacity building is crucial for the successful implementation of these practices (Tilman et al., 2020).
The findings of this study contribute to the growing body of evidence supporting the strategic management of nitrogen in soybean cultivation. By elucidating the interactions between nitrogen application, climatic factors, and crop performance, this research aims to empower farmers with actionable insights to navigate the challenges of a changing climate. Furthermore, the study underscores the importance of integrating agronomic, environmental, and socio-economic considerations into fertilization strategies, paving the way for resilient and sustainable agricultural systems in Romania and beyond.

## MATERIALS AND METHODS

### Experimental period and locations

In the spring of 2024, both locations Caracal and Crişcior experienced difficult climate conditions. As shown in Figure 1, the temperatures during the growing season were higher than usual, which resulted in delays in soybean planting. Consequently, the soybean growing season in these areas was restricted to a narrower timeframe, specifically between the second half of April and the second half of September. During this period, the precipitation levels, presented in Figure 2, were also insufficient to support optimal soybean growth.

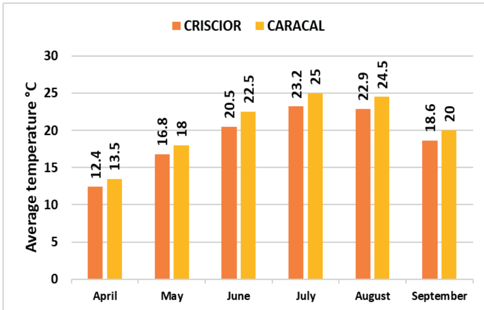


Figure 1. The average temperature during the growing season of 2024 (https://freemeteo.com/frame.asp?ifrid=236788_cazare-ranca.ro&pid)

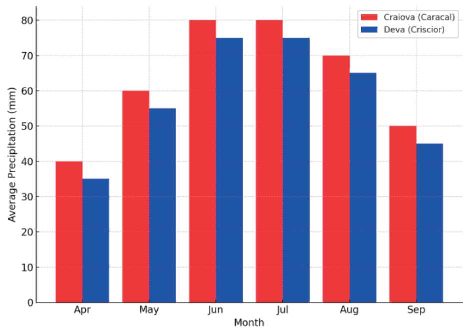


Figure 2. Average precipitation during the growing season of 2024 (https://www.meteoblue.com/ro/%20vreme/historyclimate/weatherarchive/romania)

As shown in Table 1, the soil in Caracal presents significantly more favorable conditions for soybean cultivation than that in Crişcior. With a slightly alkaline pH, higher levels of nitrogen, phosphorus, and potassium, and its classifycation as a clay-illuvial Chernozem, the Caracal soil offers optimal conditions for soybean growth, supporting good root development and nutrient uptake. In contrast, the podzolic soil in Crișcior, characterized by higher acidity and lower nutrient availability, is less suitable for soybeans unless properly amended.

Table 1. Soil Properties in CARACAL and CRIȘCIOR – 2024

| Location | CARACAL | CRIȘCIOR |
|---|---|---|
| Year | 2024 | 2024 |
| pH (water) | 7.6 | 6.2 |
| Humus (%) | 2,58 | 2.51 |
| Total N (%) | 0,189 | 0.15 |
| P (ppm) | 93 | 33 |
| K (ppm) | 235 | 166 |
| Soil type | Clay-illuvial Chernozem | Podzolic |

This limited growing window impacted the development of the crop, shortening the overall vegetation period and potentially affecting yields due to the reduced time available for the plants to grow and mature.

**Soybean varieties**

This study examines the performance of different soybean varieties in various regions of Romania. Below, we present the four varieties selected for our experiment.

The **Orakel PZO** soybean variety is a moderate type with strong production potential, classified in maturity group 00, similar to wheat in its growth cycle.

Yields typically range from 3000-3500 kg/ha but can exceed 4500 kg/ha in favorable conditions(https://ig-pflanzenzucht.de/wp-content/plugins/igp-filter/tpl/saatgut-generate-pdf.php).

For sowing, it is recommended to follow the optimal period based on local conditions, use a seeding density of 60-65 viable seeds per square meter, and adjust the seeding depth according to soil type. Orakel PZO is well-suited for farmers seeking reliable, high-quality harvests in a variety of climates.

**Amiata** is an early soybean variety in maturity group 00, highly adaptable to various cultivation conditions and known for its outstanding traits.

It has indeterminate growth, early flowering and harvesting, medium to tall plants, and violet-colored flowers.

The beans weigh 170-210 grams, with high fat content (over 20%) and protein levels (over 40%), along with an open hilum (https://binealegibineculegi.ro/pdf/?id=9296)

Amiata demonstrates strong vigor, resistance to shattering and lodging, and high yield potential. It is resilient, showing good tolerance to diseases and challenging environmental conditions.

The ideal sowing period is between late April and mid-May, with recommended row spacing of 15-24 cm. Thanks to its early maturity, harvesting can be done in a short timeframe.

**Used techniques**

This study examines the impact of climate variations and fertilizer application on soybean cultivation in southern and central Romania. Experimental plots were established in these regions, applying different fertilizer types and quantities.

Plant development and yields were monitored throughout the growing season, with data analyzed to identify trends and correlations between climate, fertilization, and crop performance.

Key measurements included plant height, the height of the first pod, and the number of pods per plant. Additionally, analyses were conducted to determine moisture levels, hectoliter weight, and oil and protein content, providing a comprehensive evaluation of crop quality and productivity.

The results offer valuable insights for improving agricultural techniques and optimizing soybean production in Romania.

The collected data and graphical representtations, created using Excel from the Office 365 suite, serve as valuable tools for enhancing agricultural practices and optimizing future production.

The correlations were also performed using Excel, while the ANOVA analysis was conducted with the help of a Python program, which can be accessed at the following link-: https://replit.com/@raulcristian19/ThreeWayAnova.

## RESULTS AND DISCUSSIONS

**Results**

Soybeans, as leguminous plants, has a unique ability to fix atmospheric nitrogen through symbiosis with rhizobia bacteria. This allows them to partially meet their nitrogen needs. However, soil nitrogen levels still influence their growth and yield, requiring careful management to maintain a balance between nitrogen fixation and soil nutrient availability. (Rymuza et al., 2020).

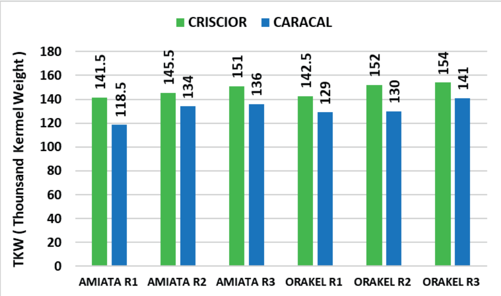


Figure 3. Thousand kernel weight across all two regions

In Figure 3 we illustrated the effects of nitrogen application rates on the Thousand Kernel Weight of two soybean varieties, Amiata and Orakel. The nitrogen rates were applied in three quantities: R1 (75 kg N/ha), R2 (125 kg N/ha), and R3 (150 kg N/ha). The Thousand Kernel Weight was higher for Amiata compared to Orakel in all nitrogen treatments. At the lowest nitrogen level (R1), Amiata reached a TKW of 141.5 g, while Orakel had 118.5 g. This pattern continued at higher nitrogen doses. At R2 (125 kg N/ha), Amiata's TKW increased to 145.5 g, while Orakel reached 134 g. At the highest nitrogen level (R3, 150 kg N/ha), Amiata had its highest TKW of 151 g, and Orakel reached 136 g.

Table 2. Thousand kernel weight correlation

| AMIATA | | | | |
|---|---|---|---|---|
| **Region** | **Repetiton** | **TKW** | **TKW Correlation** | **N applied** |
| Criscior | R1 | 141.5 | 0.960768923 | 75 |
| | R2 | 145.5 | | 125 |
| | R3 | 151 | | 150 |
| Caracal | R1 | 118.5 | 0.973920338 | 75 |
| | R2 | 134 | | 125 |
| | R3 | 136 | | 150 |
| **ORAKEL** | | | | |
| **Region** | **Repetiton** | **TKW** | **TKW Correlation** | **N applied** |
| Criscior | R1 | 142.5 | 0.985586763 | 75 |
| | R2 | 152 | | 125 |
| | R3 | 154 | | 150 |
| Caracal | R1 | 129 | 0.802955069 | 75 |
| | R2 | 130 | | 125 |
| | R3 | 141 | | 150 |

Even though these differences were not statistically significant according to the ANOVA analysis shown in Table 3 ($p > 0.05$), the results still show a clear trend as it can be seen in Table 3.

Table 3. Thousand kernel weight ANOVA analysis

| Variation source | Sum of squares | Degrees of freedom | F - statistic | p-value |
|---|---|---|---|---|
| Intercept | 140185.6 | 1 | 20.176 | 0.00002 |
| Genotype | 2668.05 | 1 | 0.384 | 0.53677432 |
| Region | 684.45 | 1 | 0.0985 | 0.75423022 |
| Nitrogen | 1861.26 | 2 | 0.1339 | 0.87478547 |
| Genotype x Region x Nitrogen | 1804.51 | 2 | 0.1299 | 0.87835657 |
| Residual | 750385 | 108 | | |

The correlation between TKW and nitrogen amount presented in Table 2 was very strong, with $r > 0.96$ for Amiata and $r = 0.80–0.98$ for Orakel as it can be seen in Table 2. This suggests a positive relationship between nitrogen application and kernel weight for both genotypes. Amiata showed a steady and stronger increase in TKW as nitrogen levels rose, suggesting it is better at using nitrogen efficiently.

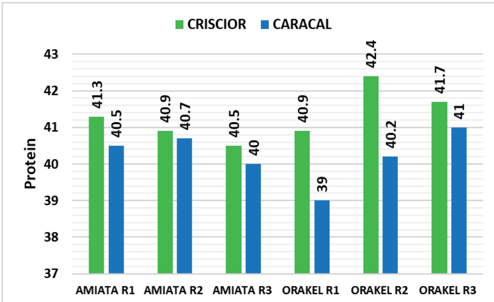


Figure 4. Protein content of soybeans across all two regions

The analysis of protein content presented in Figure 4, for the Amiata and Orakel varieties grown in Crişcior and Caracal, reveals distinct regional and varietal trends. In Crişcior, Amiata shows consistent protein levels across replicates (R1: 41.3%, R2: 40.9%, R3: 40.5%), suggesting high stability. Orakel, although more variable, reaches the highest protein value of 42.4% in R2, indicating strong potential under favorable conditions.

In Caracal, both varieties show lower protein content compared to Crişcior. Amiata's values slightly decline (R1: 40.5%, R2: 40.7%, R3: 40%), maintaining overall stability. Orakel displays greater sensitivity, with R1 dropping to 39%, R2 at 40.2%, and R3 improving to 41%. This suggests that Crişcior offers a more favorable environment, especially for Orakel, which is more responsive to regional conditions.

Table 4. Protein correlation

| AMIATA | | | | |
|---|---|---|---|---|
| **Region** | **Repetiton** | **Protein** | **Protein correlation** | **N applied** |
| Criscior | R1 | 41.3 | -0.981980506 | 75 |
| | R2 | 40.9 | | 125 |
| | R3 | 40.5 | | 150 |
| Caracal | R1 | 40.5 | -0.544704779 | 75 |
| | R2 | 40.7 | | 125 |
| | R3 | 40 | | 150 |
| **ORAKEL** | | | | |
| **Region** | **Repetiton** | **Protein** | **Protein correlation** | **N applied** |
| Criscior | R1 | 40.9 | 0.68324347 | 75 |
| | R2 | 42.4 | | 125 |
| | R3 | 41.7 | | 150 |
| Caracal | R1 | 39 | 0.997176465 | 75 |
| | R2 | 40.2 | | 125 |
| | R3 | 41 | | 150 |

Despite these trends, the ANOVA analysis presented in Table 5 revealed no statistically significant differences in protein content by genotype (F = 0.008, p = 0.9288), region (F = 0.019, p = 0.8894), nitrogen levels (F = 0.0014, p = 0.9986), or their interaction (F = 0.032, p = 0.9968).

Table 5. Protein ANOVA analysis

| Variation source | Sum of squares | Degrees of freedom | F - statistic | p-value |
|---|---|---|---|---|
| Intercept | 16321.6 | 1 | 32.3491 | 0.0000001 |
| Genotype | 4.05 | 1 | 0.008 | 0.9288 |
| Region | 9.8 | 1 | 0.0194 | 0.8894 |
| Nitrogen | 1.4 | 2 | 0.0014 | 0.9986 |
| Genotype x Region x Nitrogen | 3.2167 | 2 | 0.0032 | 0.9968 |
| Residual | 54490.9 | 108 | | |

However, correlation analyses between nitrogen application and protein content from Table 4 revealed notable patterns. For Amiata, strong negative correlations were observed in both Crişcior (r = –0.98) and Caracal (r = –0.54), suggesting a decrease in protein with increasing nitrogen. Orakel showed a positive correlation in Crişcior (r = 0.68) but a strong negative one in Caracal (r = –0.99), indicating location-dependent variability.

The data presented in Figure 5 illustrate variations in oil content for the two soybean genotypes, Amiata and Orakel, cultivated in the Crişcior and Caracal regions. In Crişcior, Amiata displayed moderate variability among replicates: R1 recorded 20.8%, R2 reached 21.5%, and R3 showed the lowest value at 20.3%. Orakel exhibited both higher oil content and slightly greater variability. Orakel R1 achieved the highest oil value in Crişcior (21.9%), R2 dropped to 20.6%, and R3 balanced between the two extremes at 21.4%. In Caracal, both genotypes showed improved oil content compared to Crişcior. Amiata recorded consistent gains, with R1 and R2 at 21.4%, and R3 reaching 21.8%. Orakel also improved, with R1 at 22%, R2 at 22.1% (the highest value across all samples), and R3 at 21.6%.

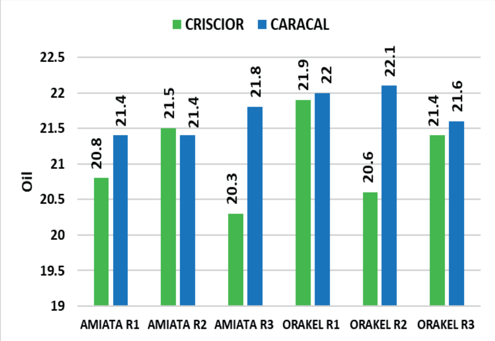


Figure 5. Oil content of soybeans across all two regions

However, correlation analyses between nitrogen levels and oil content suggest nuanced patterns. For Amiata, a slightly negative correlation was observed in Criscior (r = –0.253), while a positive correlation emerged in Caracal (r = 0.756). Orakel showed negative correlations in both regions: r = –0.549 in Criscior and r = –0.616 in Caracal (Table 6).

Table 6. Oil content correlation

| AMIATA | | | | |
|---|---|---|---|---|
| **Region** | **Repetiton** | **Oil** | **Oil Correlation** | **N applied** |
| Criscior | R1 | 20.8 | -0.2353158 | 75 |
| | R2 | 21.5 | | 125 |
| | R3 | 20.3 | | 150 |
| Caracal | R1 | 21.4 | 0.755928946 | 75 |
| | R2 | 21.4 | | 125 |
| | R3 | 21.8 | | 150 |
| **ORAKEL** | | | | |
| **Region** | **Repetiton** | **Oil** | **Oil Correlation** | **N applied** |
| Criscior | R1 | 21.9 | -0.549085619 | 75 |
| | R2 | 20.6 | | 125 |
| | R3 | 21.4 | | 150 |
| Caracal | R1 | 22 | -0.618589574 | 75 |
| | R2 | 22.1 | | 125 |
| | R3 | 21.6 | | 150 |

Despite these observed trends in Table 7, the ANOVA analysis revealed no statistically significant differences in oil content based on genotype, location, or nitrogen level. All p-values were well above the 0.05 threshold: genotype (F = 0.0149, p = 0.9029), location (F = 0.0149, p = 0.9029), nitrogen (F = 0.0051, p = 0.9949), and the three-way interaction (F = 0.0381, p = 0.9626).

Table 7. Oil content ANOVA analysis

| Variation source | Sum of squares | Degrees of freedom | F - statistic | p-value |
|---|---|---|---|---|
| Intercept | 4579.6 | 1 | 27.9143 | 0.0000006 |
| Genotype | 2.45 | 1 | 0.0149 | 0.903 |
| Region | 2.45 | 1 | 0.0149 | 0.903 |
| Nitrogen | 16.667 | 2 | 0.0051 | 0.9949 |
| Genotype x Region x Nitrogen | 12.5167 | 2 | 0.0381 | 0.9626 |
| Residual | 17718.4 | 108 | | |

Figure 6 presents the test weight data for the soybean genotypes Amiata and Orakel cultivated in the regions of Crişcior and Caracal, offering insights into varietal performance and environmental responses. In Criscior, Amiata exhibited moderate variability across its three replicates, with R1 recording 69.12 kg/hL, R2 peaking at 71.88 kg/hL, and R3 reaching the lowest value at 68.96 kg/hL. Orakel demonstrated slightly less results and generally higher test weight values: 70.24 kg/hL (R1), 71.55 kg/hL (R2), and 70.55 kg/hL (R3), consistently outperforming Amiata in this region.

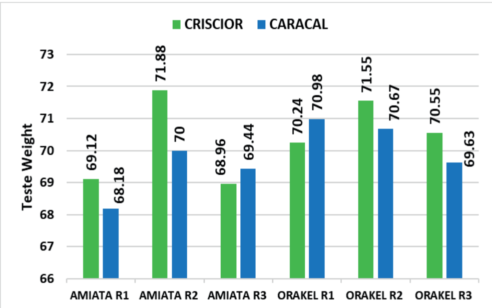


Figure 6. Test weight of soybeans across all two regions

In Caracal, both genotypes recorded slightly lower test weights compared to Crişcior. Amiata R1 measured 68.18 kg/hL, R2 achieved 70.00 kg/hL, and R3 reached 69.44 kg/hL, reflecting a minor decline. Similarly, Orakel maintained its superior performance, with R1 at 70.98 kg/hL - the highest among all Caracal replicates - R2 at 70.67 kg/hL, and R3 at 69.63 kg/hL

Table 8. Test weight correlation

| AMIATA | | | | |
|---|---|---|---|---|
| Region | Repetiton | Test weight | Test weight Correlation | N applied |
| Criscior | R1 | 69.12 | 0.140903638 | 75 |
| | R2 | 71.88 | | 125 |
| | R3 | 68.96 | | 150 |
| Caracal | R1 | 68.18 | 0.802955069 | 75 |
| | R2 | 70 | | 125 |
| | R3 | 69.44 | | 150 |
| ORAKEL | | | | |
| Region | Repetiton | Test weight | Test weight Correlation | N applied |
| Criscior | R1 | 70.24 | 0.406399402 | 75 |
| | R2 | 71.55 | | 125 |
| | R3 | 70.55 | | 150 |
| Caracal | R1 | 70.98 | -0.881042761 | 75 |
| | R2 | 70.67 | | 125 |
| | R3 | 69.63 | | 150 |

Statistical analysis through ANOVA revealed no significant effects of genotype as it can be senn o Table 9, region, or nitrogen level on test weight. The p-values were well above the 0.05 threshold: genotype (F = 0.0023, p = 0.9622), region (F = 0.0203, p = 0.887), nitrogen (F = 0.0054, p = 0.9946), and the interaction between all three factors (F = 0.0018, p = 0.9982). These results confirm the absence of statistically significant influences on test weight from the experimental factors.

Table 9. Test weight ANOVA analysis

| Variation source | Sum of squares | Degrees of freedom | F - statistic | p-value |
|---|---|---|---|---|
| Intercept | 46512.4 | 1 | 25.8812 | 0.0000002 |
| Genotype | 4.05 | 1 | 0.0023 | 0.9622 |
| Region | 36.45 | 1 | 0.0203 | 0.887 |
| Nitrogen | 194.667 | 2 | 0.0054 | 0.9946 |
| Genotype x Region x Nitrogen | 6.4667 | 2 | 0.0018 | 0.9982 |
| Residual | 194092.5 | 108 | | |

Yet, correlation analysis from Table 8 suggests subtle trends. For Amiata, a weak positive correlation was observed in Crişcior (r = 0.14), and a moderate one in Caracal (r = 0.80), implying a potential increase in test weight with higher nitrogen doses, particularly under Caracal conditions.

Orakel, on the other hand, displayed a positive correlation in Crişcior (r = 0.40) and a strong negative correlation in Caracal (r = –0.88), indicating contrasting responses depending on location. These findings suggest a possible interaction between nitrogen, genotype, and environment, though not supported by statistically significant differences.

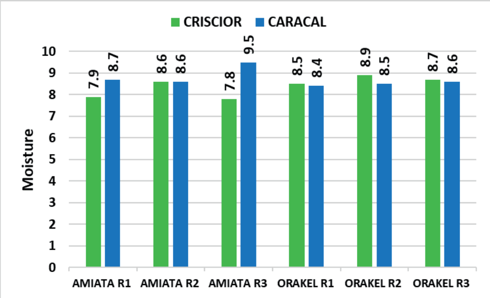


Figure 7. Moisture of soybeans across all two regions

Figure 7 presents the analysis of moisture content in the soybean varieties Amiata and Orakel, cultivated in the regions of Crișcior and Caracal. Although the descriptive statistics reveal noticeable variation between the two varieties and across the two locations, inferential statistical analysis indicates that these differences are not statistically significant.

Table 10. Moisture correlation

| AMIATA | | | | |
|---|---|---|---|---|
| **Region** | **Repetiton** | **Moisture** | **Moisture Correlation** | **N applied** |
| Criscior | R1 | 7.9 | 0.97622104 | 75 |
| | R2 | 8.6 | | 125 |
| | R3 | 8.7 | | 150 |
| Caracal | R1 | 8.7 | 0.685679631 | 75 |
| | R2 | 8.6 | | 125 |
| | R3 | 9.5 | | 150 |
| **ORAKEL** | | | | |
| **Region** | **Repetiton** | **Moisture** | **Moisture Correlation** | **N applied** |
| Criscior | R1 | 8.5 | 0.654653671 | 75 |
| | R2 | 8.9 | | 125 |
| | R3 | 8.7 | | 150 |
| Caracal | R1 | 8.4 | 0.981980506 | 75 |
| | R2 | 8.5 | | 125 |
| | R3 | 8.6 | | 150 |

The ANOVA results from Table 11 reveal no statistically significant differences in moisture content between genotypes, locations, nitrogen levels, or their interactions. The p-values were high across all factors: genotype ($F = 0.067$, $p = 0.9622$), location ($F = 0.186$, $p = 0.887$), nitrogen treatment ($F = 0.0645$, $p = 0.9946$), and the three-way interaction ($F = 0.0645$, $p = 0.9982$). These results suggest that none of the examined variables had a statistically measurable impact on moisture content at the chosen significance level.

However, correlation analysis from Table 10 between applied nitrogen levels and moisture content reveals consistent positive trends, indicating a possible physiological influence not captured through ANOVA. For the Amiata genotype, very strong and positive correlations were observed: $r = 0.9762$ in Criscior and $r = 0.6857$ in Caracal. Similarly, Orakel showed strong correlations: $r = 0.6547$ in Criscior and $r = 0.9820$ in Caracal. These values suggest that increased nitrogen application tends to elevate moisture content, likely due to enhanced water retention in the seeds.

Table 11. Moisture ANOVA analysis

| Variation source | Sum of squares | Degrees of freedom | F - statistic | p-value |
|---|---|---|---|---|
| Intercept | 774.4 | 1 | 28.8192 | 0.0000002 |
| Genotype | 1.8 | 1 | 0.067 | 0.9622 |
| Region | 5 | 1 | 0.186 | 0.887 |
| Nitrogen | 3.4667 | 2 | 0.645 | 0.9946 |
| Genotype x Region x Nitrogen | 3.4667 | 2 | 0.0645 | 0.9982 |
| Residual | 2902.7 | 108 | | |

Although not statistically significant in a strict sense, the consistently strong correlation coefficients support the hypothesis of a physiological response of soybean seeds to nitrogen fertilization in terms of moisture accumulation. This trend is especially evident for both genotypes in Caracal, where environmental conditions may further accentuate nitrogen's effect on seed hydration.

The bar chart from Figure 8 illustrates the average plant height of two soybean varieties, Amiata and Orakel, across three replications (R1-R3) in the regions of Crișcior and Caracal. Overall, higher plant heights are recorded in Caracal compared to Crișcior, suggesting that the environmental and soil conditions in Caracal may have a more favorable effect on the vegetative growth of soybean plants.

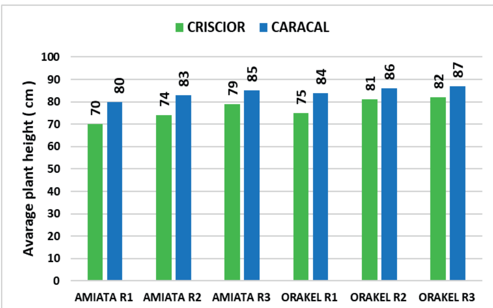


Figure 8. The average height of soybean plants across all two regions

The bar chart from Figure 8 illustrates the average plant height of two soybean varieties, Amiata and Orakel, across three replications (R1-R3) in the regions of Crişcior and Caracal. Overall, higher plant heights are recorded in Caracal compared to Crişcior, suggesting that the environmental and soil conditions in Caracal may have a more favorable effect on the vegetative growth of soybean plants.

The analysis of variance (ANOVA) for average plant height, Table12, revealed no statistically significant effects among the tested factors. The p-values were notably high across all variables: region ($F = 0.166$, $p = 0.6843$), fertilization type ($F = 0.021$, $p = 0.9788$), genotype ($F = 0.0258$, $p = 0.8727$), and the three-way interaction ($F = 0.0026$, $p = 0.9974$).

These results indicate that neither genotype, region, nor nitrogen application levels had a statistically significant impact on plant height.

Table 12. The average height of soybean plants ANOVA analysis

| Variation source | Sum of squares | Degrees of freedom | F - statistic | p-value |
|---|---|---|---|---|
| Intercept | 64000 | 1 | 21.7026 | 0.0000009 |
| Genotype | 76.05 | 1 | 0.0258 | 0.8727 |
| Region | 490.05 | 1 | 0.1662 | 0.6843 |
| Nitrogen | 126.6667 | 2 | 0.0215 | 0.9788 |
| Genotype x Region x Nitrogen | 15.5167 | 2 | 0.0026 | 0.9974 |
| Residual | 318487.4 | 108 | | |

Table 13. The average height of soybean plants correlation

| AMIATA | | | | |
|---|---|---|---|---|
| Region | Repetiton | Avarage height | Avarage height Correlation | N applied |
| Criscior | R1 | 70 | 0.967867837 | 75 |
| | R2 | 74 | | 125 |
| | R3 | 79 | | 150 |
| Caracal | R1 | 80 | 0.997176465 | 75 |
| | R2 | 83 | | 125 |
| | R3 | 85 | | 150 |
| ORAKEL | | | | |
| Region | Repetiton | Avarage height | Avarage height Correlation | N applied |
| Criscior | R1 | 75 | 0.97986371 | 75 |
| | R2 | 81 | | 125 |
| | R3 | 82 | | 150 |
| Caracal | R1 | 84 | 1 | 75 |
| | R2 | 86 | | 125 |
| | R3 | 87 | | 150 |

Despite the lack of statistical significance in the ANOVA results, the correlation analysis presented in Table 13 revealed strong and consistent positive relationships between nitrogen application and plant height. For the Amiata genotype, correlation coefficients were $r = 0.9678$ in Crişcior and $r = 0.9971$ in Caracal, suggesting a near-linear increase in height with increasing nitrogen levels. Similarly, the Orakel genotype showed extremely strong correlations: $r = 0.9798$ in Criscior and $r = 1.0000$ in Caracal.

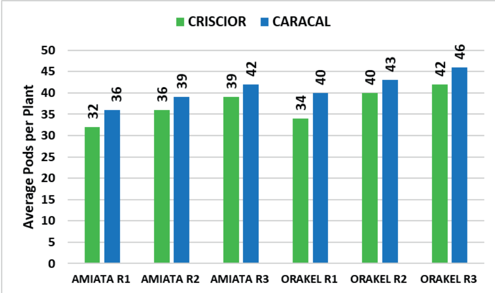


Figure 9. Avarage pods per plant across all two regions

The average number of pods per plant for the soybean varieties Amiata and Orakel, across three replications (R1-R3), is presented in the Figure 9. A consistent increase in pod number is observed in Caracal compared to Crişcior, indicating that the environmental and soil conditions in Caracal are more conducive to the reproductive performance of soybean plants.

Table14. Average pods per plant correlation

| AMIATA | | | | |
|---|---|---|---|---|
| Region | Repetiton | Avarage pods | Avarage pods Correlation | N applied |
| Criscior | R1 | 32 | 0.994191626 | 75 |
| | R2 | 36 | | 125 |
| | R3 | 39 | | 150 |
| Caracal | R1 | 36 | 0.981980506 | 75 |
| | R2 | 39 | | 125 |
| | R3 | 42 | | 150 |
| ORAKEL | | | | |
| Region | Repetiton | Avarage pods | Avarage pods Correlation | N applied |
| Criscior | R1 | 34 | 0.995870595 | 75 |
| | R2 | 40 | | 125 |
| | R3 | 42 | | 150 |
| Caracal | R1 | 40 | 0.981980506 | 75 |
| | R2 | 43 | | 125 |
| | R3 | 46 | | 150 |

Table 15. Average pods per plant ANOVA analysis

| Variation source | Sum of squares | Degrees of freedom | F - statistic | p-value |
|---|---|---|---|---|
| Intercept | 13032.1 | 1 | 22.8377 | 0.0000006 |
| Genotype | 84.05 | 1 | 0.1473 | 0.7019 |
| Region | 174.2 | 1 | 0.1526 | 0.8586 |
| Nitrogen | 72.2 | 2 | 0.1265 | 0.7228 |
| Genotype x Region x Nitrogen | 4.05 | 2 | 0.0035 | 0.9965 |
| Residual | 61629.1 | 108 | | |

The analysis of variance (ANOVA) for the average number of pods per plant, as shown in Table 15, did not reveal statistically significant

differences among the analyzed factors. High p-values were recorded for all variables: genotype ($F = 0.147$, $p = 0.7019$), region ($F = 0.152$, $p = 0.8586$), nitrogen application rate ($F = 0.126$, $p = 0.7228$), and the three-way interaction ($F = 0.0035$, $p = 0.9965$).
On the same time, correlation analysis between the average number of pods and the nitrogen application rate revealed a strong positive relationship in all cases as it can be seen in Table14. For the Amiata genotype, extremely high correlation coefficients were found: $r = 0.994$ in Crişcior and $r = 0.981$ in Caracal, suggesting a significant increase in pod production with higher nitrogen doses. Similarly, the Orakel genotype showed very high correlations as well: $r = 0.995$ in Crişcior and $r = 0.981$ in Caracal.
Despite the ANOVA results did not indicate statistical significance, the consistently strong positive correlations point to a clear physiological effect of nitrogen fertilization on pod development.

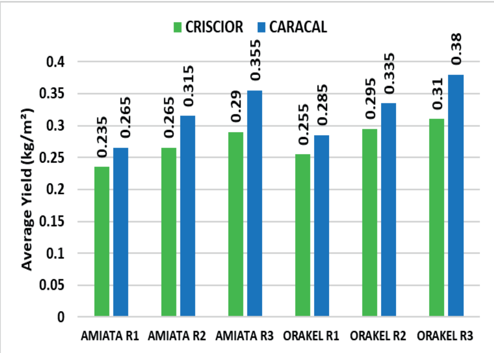


Figure 10. The average grain yield across all two regions

In the 2024 growing season, both Amiata and Orakel soybean varieties demonstrated significant yield improvements with increasing nitrogen application in the regions of Crişcior and Caracal, as shown in Figure 10. In Crişcior, Amiata's yield increased progressively with higher fertilizer rates, from 0.235 kg/m² at 75 kg/ha to 0.29 kg/m² at 150 kg/ha. Orakel outperformed Amiata, achieving 0.31 kg/m² at 150 kg/ha.
In Caracal, both varieties showed better yields compared to Criscior, with Amiata reaching up to 0.355 kg/m² at 150 kg/ha and Orakel achieving 0.38 kg/m² at the same rate.

Table 16. The average grain yield correlation

| AMIATA | | | | |
|---|---|---|---|---|
| **Region** | **Repetiton** | **Grain yield** | **Grain yeald - Correlation** | **N applied** |
| Criscior | R1 | 0.235 | 0.990536065 | 75 |
| | R2 | 0.265 | | 125 |
| | R3 | 0.29 | | 150 |
| Caracal | R1 | 0.265 | 0.992064533 | 75 |
| | R2 | 0.315 | | 125 |
| | R3 | 0.355 | | 150 |
| **ORAKEL** | | | | |
| **Region** | **Repetiton** | **Grain yield** | **Grain yeald - Correlation** | **N applied** |
| Criscior | R1 | 0.255 | 0.997788423 | 75 |
| | R2 | 0.295 | | 125 |
| | R3 | 0.31 | | 150 |
| Caracal | R1 | 0.285 | 0.987267385 | 75 |
| | R2 | 0.335 | | 125 |
| | R3 | 0.38 | | 150 |

Correlations between nitrogen application and bean yield were strong for both varieties and regions, indicating a consistent positive response to nitrogen fertilization. For Amiata, correlation coefficients were $r = 0.9905$ in Criscior and $r = 0.9921$ in Caracal. For Orakel, they were $r = 0.9978$ in Criscior and $r = 0.9873$ in Caracal (Table 16).
These strong correlations confirm that nitrogen fertilization is crucial for maximizing yield potential, with Orakel showing superior productivity in both regions.
In Crişcior, the average number of branches per plant varied for both the Amiata and Orakel varieties as it cand be seen in Figure 11. For Amiata, the number of branches increased from 2.3 for Amiata R1 (75 kg/ha) to 2.7 for Amiata R2 (125 kg/ha), reaching a peak of 3 branches per plant for Amiata R3 (150 kg/ha) as shown in Figure 11.

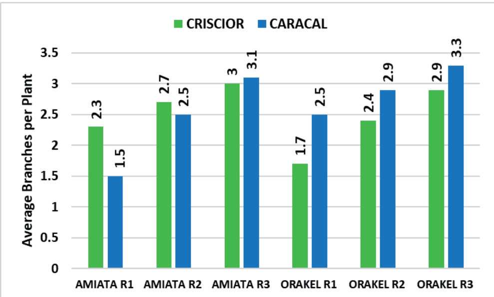


Figure11. The average number of branches per plant across all two regions

Similarly, in Orakel, the number of branches improved as the fertilizer rate increased, with Orakel R1 (75 kg/ha) producing 1.7 branches, Orakel R2 (125 kg/ha) producing 2.4 branches, and Orakel R3 (150 kg/ha) reaching 2.9 branches per plant (figure 11). Despite these increases, Orakel consistently had fewer branches compared to Amiata under the same conditions in Criscior.

In Caracal, both varieties exhibited distinct branching patterns. Amiata, for example, had fewer branches in Caracal compared to Crişcior, with Amiata R1 (75 kg/ha) producing just 1.5 branches per plant. However, as fertilizer application increased, branching improved, with Amiata R3 (150 kg/ha) reaching 3.1 branches per plant, slightly surpassing the maximum observed in Criscior. In contrast, Orakel performed better in Caracal than in Crişcior, with Orakel R1 (75 kg/ha) producing 2.5 branches, and Orakel R3 (150 kg/ha) achieving 3.3 branches per plant. This improvement highlights the beneficial environmental conditions in Caracal for Orakel.

Table 17. The average number of branches per plant correlation

| AMIATA | | | | |
|---|---|---|---|---|
| Region | Repetiton | Branches | Branches Correlation | N applied |
| Criscior | R1 | 2.3 | 0.994191626 | 75 |
| | R2 | 2.7 | | 125 |
| | R3 | 3 | | 150 |
| Caracal | R1 | 1.5 | 0.998906107 | 75 |
| | R2 | 2.5 | | 125 |
| | R3 | 3.1 | | 150 |
| ORAKEL | | | | |
| Region | Repetiton | Branches | Branches Correlation | N applied |
| Criscior | R1 | 1.7 | 0.995566845 | 75 |
| | R2 | 2.4 | | 125 |
| | R3 | 2.9 | | 150 |
| Caracal | R1 | 2.5 | 0.981980506 | 75 |
| | R2 | 2.9 | | 125 |
| | R3 | 3.3 | | 150 |

Table 18. The average number of branches per plant ANOVA analysis

| Variation source | Sum of squares | Degrees of freedom | F - statistic | p-value |
|---|---|---|---|---|
| Intercept | 19.6 | 1 | 10.341 | 0.0017 |
| Genotype | 4.05 | 1 | 2.1368 | 0.1467 |
| Region | 7.2 | 1 | 3.7987 | 0.0539 |
| Nitrogen | 14.8667 | 2 | 3.9218 | 0.0227 |
| Genotype x Region x Nitrogen | 2.2167 | 2 | 0.5848 | 0.559 |
| Residual | 204.7 | 108 | | |

The ANOVA analysis presented in Table 18 confirmed that nitrogen application had a significant effect on the number of branches ($F = 3.92$, $p = 0.0227$), further supporting the positive response of branching to increased fertilizer levels. The region factor also approached significance ($F = 3.798$, $p = 0.0539$), indicating that environmental conditions could influence branching development. However, genotype ($F = 2.136$, $p = 0.1467$) and the triple interaction ($F = 0.58$, $p = 0.559$) did not significantly affect branching.

High correlations were observed in Table 17 between the number of branches and nitrogen application, with Amiata showing $r = 0.9941$ in Criscior and $r = 0.9989$ in Caracal. For Orakel, correlations were similarly high, with $r = 0.9955$ in Crişcior and $r = 0.981$ in Caracal, confirming that nitrogen fertilization significantly stimulates branching. These results underline the biological and statistical significance of nitrogen fertilization in enhancing plant development, especially in terms of branching.

## DISCUSSIONS

This study builds upon previous research conducted in 2024 titled "Analyzing the Impact of Climate Variations and Fertilizer Application on Soybean Cultivation across Western, Southern, and Central Romania". (Jurcut et al., 2024) While the earlier work provided valuable insights into regional differences in soybean performance and highlighted the influence of environmental and fertilization factors, it lacked statistical analysis, limiting the interpretation of result significance.

The current study represents a continuation and deepening of that research, focusing specifically on the Southern and Central regions (Caracal and Crişcior) and incorporating a robust statistical framework. By introducing ANOVA and correlation analyses, the study not only confirms trends observed previously - such as improved productivity with nitrogen application and the influence of regional agro-environmental conditions - but also quantifies the strength of these relationships. Despite most results not reaching statistical significance, strong positive correlations were consistently found between nitrogen levels and key agronomic traits such as grain yield, plant height, number of pods, and branching.

These findings reinforce the importance of context-specific nitrogen management in soybean cultivation and provide a more rigorous foundation for optimizing fertilization strategies under the pressures of climate variability in Romania.

## CONCLUSIONS

Nitrogen fertilization proved essential for enhancing soybean productivity, with all measured traits - plant height, number of pods, grain yield, and branching - showing strong positive correlations with increasing nitrogen levels, despite the lack of statistically significant differences in most ANOVA tests.

Statistical analysis using ANOVA did not indicate significant effects ($p > 0.05$) of nitrogen rate, genotype, or location on most traits, suggesting that high variability and environmental interactions may obscure measurable differences at conventional significance thresholds.

Correlation analysis revealed consistently strong and positive relationships between nitrogen application and key agronomic indicators, particularly in plant height ($r > 0.96$), pod number ($r > 0.98$), and grain yield ($r > 0.98$), supporting the physiological impact of nitrogen on soybean development.

The Amiata variety exhibited better nitrogen use efficiency, with greater increases in Thousand Kernel Weight (TKW) and branching in response to higher nitrogen doses, indicating its adaptability to nitrogen-enhanced cultivation systems.

Although not statistically significant, the combined statistical and observational data support the conclusion that nitrogen fertilization plays a critical role in optimizing soybean performance under variable climatic conditions, highlighting the value of integrated fertilization strategies in climate-sensitive regions.

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