Hungarian University of Agriculture and Life Sciences

The Thesis of the PhD Dissertation

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Performance Studies of Soybean (G*lycine max* (L.) Merr.) in the Field and Using a Soilless Culture System in a Controlled Environment

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1. RESEARCH BACKGROUND AND OBJECTIVES

Soybean is a valuable crop with high nutritional and functional benefits, making it a staple in many countries' diets. With 38% protein, 27% carbohydrate, 19% oil, 12% water, and 4% ashes, soybeans are used in food production, livestock feed, and non-edible products. Soybean also improves soil fertility by fixing atmospheric nitrogen (N) and forming a symbiotic relationship with beneficial bacteria, reducing dependence on other N sources. Soybean is cultivated over 136.14 million hectares and will have a global production of 388.01 million metric tonnes in 2022/23. It is expected to reach a record 410.6 million metric tonnes in 2023/24, an 11% increase from 2022/23. To sustain or enhance soybean production, the cultivation process must consider various factors, including environmental conditions, agronomic practices, and variety selection.

The cultivation system that is widely used for soybeans is conventional in various environmental conditions. Soybean can be grown on well-drained and fertile loam soils in warm climates. This cultivation system has faced challenges due to rapid development, soil fertility decline, pests and diseases, frequent droughts, and unpredictable climate patterns. These issues impact agricultural productivity and quality. An alternative, soilless cultivation system in controlled environments is currently used for most plants. This system allows planting anywhere and anytime throughout the year and produces high and consistent yields and quality. However, the use of this approach for soybean grain yield has not been widely studied, and related information is limited and difficult to obtain.

Soybean cultivation in controlled environments allows for the manipulation of crucial factors like temperature. Optimal temperatures are crucial for developing vigorous seedlings for good growth. Variety selection is also crucial for both conventional and controlled environment systems, with short maturity periods being best suited for low-rainfall areas or late-season planting. Late mature varieties are less suitable for dry conditions but often generate higher grain, fix more N, and contribute to increasing soil fertility. Meanwhile, nutrient application, including N, is also essential for crop production and can have positive or negative effects depending on the amount, crop growth stage, combination, and balance.

Another important factor that influences soybean cultivation is weed management. It is critical when utilizing a conventional planting system. This is due to competition between soybeans and weeds for input sources such as nutrients. When weeds are not controlled efficiently, nutrient application can encourage weed growth rather than crop yield. Therefore, it is important to investigate the impact of weed management on soybean cultivation, particularly in open-field planting and for specific varieties.

Thus, three experiments were conducted on the important factors that affect the growth, yield, and quality of soybeans in both cultivation systems: open field (one experiment) and controlled environment (two experiments). The general aim of these studies is to investigate the performance of soybean varieties in the field and using a soilless culture system in a controlled environment as influenced by factors such as nutrients, weed canopy, variety, and temperature. The specific objectives are specified as follows:

i. To evaluate the effect of nitrogen nutrition and weed canopy on yield formation and chemical composition of soybeans grown in the field
ii. To investigate the influence of temperature and variety in a controlled growth chamber on the germination rate, seedling length, and viability of soybeans
iii. To study the response of growth, yield components, yield, and chemical compositions to the nutrient concentration of two soybean varieties grown under soilless and controlled environment conditions

2. MATERIALS AND METHODS

2.1 Experimental Research 1: Effect of nitrogen application and weed canopy on yield formation and chemical composition of soybeans under open-field planting

In May 2020, a field experiment was conducted at the Institute of Agronomy, Hungarian University of Agriculture and Life Sciences (MATE), Gödöllő, Hungary, to achieve the first objective of this study. The soil type was brown forest soil. A soybean variety, ES Gladiator, was planted with a scheduled plant density of 540,000 viable germs per hectare. The experiment involved two nitrogen (N) rates (0 and 200 kg N/ha) and three weed canopy treatments (weedy, hand weeded, and mechanically weeded). The N fertilizer source was ammonium nitrate, applied once at 60 days after sowing. The weed canopy treatments were done every two weeks, with mechanically weeded treatments using an inter-row handy hoeing machine. The experimental design utilized a split plot with four replications, assigning N application to the main plot and the weed canopy to the sub-plot.

The plant harvesting involved a 1.5 m^2 sampling area per plot to calculate grain yield. The grains were ground for determination of protein and lipid content using the NIR Product Analyzer. All the data were statistically analyzed using SPSS software. A one-way ANOVA was conducted to compare the effects of N supply and weed canopy on all parameters.

2.2 Experimental Research 2: Influence of temperature and varieties on seed germination of soybeans at different germination times

The second experiment was designed to meet the second objective of this study. The study was conducted at the Crop Production Laboratory of the Institute of Agronomy, MATE, Gödöllő to investigate the impact of temperature, variety, and germination time on soybean seed germination. Two soybean varieties, Martina and Johanna, were tested and placed in Petri dishes, exposed to three different temperatures (15, 25, and 35 °C) in different plant growth chambers. The data were recorded at four germination times (3, 5, 7, and 9 days after sowing). The experiment was conducted using a randomized complete block design with four replicates.

The study recorded data on germination rate (%), total seedling length (cm), and viability (%). Viability was recorded on day 12 after sowing. In this experiment, viability refers to the ability of seeds to germinate, survive, and produce healthy seedlings that were recorded when the germinated seeds produced a shoot (plumule). The data was analyzed using SPSS software, and a three-way ANOVA was used. The LSD test was then applied to compare treatment mean differences at a probability level of 0.05.

2.3 Experimental Research 3: Response of growth, yield, and chemical composition to nutrient concentrations of soybean varieties grown using a soilless culture system in a controlled environment

The experiment was conducted in a controlled environment growth chamber at the Institute of Agronomy, MATE, Gödöllő, from January to November 2022. The chamber, measuring 4 m x 1.8 m, was equipped with planting tools such as pots, fertilizer solution tanks, water pumps, a drip irrigation system, and a timer. 24 pots were placed on top of 4 nutrient solution tanks, with 6 pots for each tank. The chamber also had air conditioning, fluorescent lamps, fans, and an exhaust fan. The arrangement of equipment in the planting system is shown in Figure 1. The growth chamber's temperature was 22 °C during the day, 16 °C at night, and the humidity was 40-60%. Two fluorescent lamps (58 watts) with a combination of red and blue lights were installed, with the lamps automatically on and off for 16 hours (950 Lux) during the day and 8 hours at night. Pots were filled with expanded clay aggregate as a substrate. Martina and Johanna varieties were used and supplied with different nutrient solution concentrations (0, 50, 100, and 150%). The experiment was designed as a split plot with three replications, with the main plot as nutrient concentration and the variety as a sub-plot.

Figure 1. Inside the controlled growth chamber that was equipped with a complete planting system

The study used Advance Hydroponics of Holland' liquid fertilizer. The nutrient solution had a pH range of 6 to 6.5 and an EC of 1.0 to 1.8 ds/m. The fertilizer was diluted with 25 liters of water in each tank. Nutrient solutions were provided after 10 days of sowing, three times daily for 30 minutes per irrigation. The solution was manually replaced weekly to maintain the optimum EC and pH readings. Harvesting was done when the pods were completely dry. Growth data were started a week after nutrients were supplied and were collected every week until the plants produced flowers, with five weeks of measurements (Week 1, Week 2, Week 3, Week 4, and Week 5). Other data collected during and after harvest included yield components, yield, and chemical composition. The grains from each treatment were ground to measure their chemical composition, including protein and lipid content, using a NIR Product Analyzer. The data were analyzed using SPSS software and a three-way ANOVA to compare nutrient concentration, variety, and weeks' effects on vegetative growth parameters, and a two-way ANOVA for other parameters.

3. RESULTS AND DISCUSSION

3.1 Experimental Research 1: Effect of nitrogen application and weed canopy on yield formation and chemical composition of soybeans under open-field planting

3.1.1 Yield formation

The study found that plants in hand weeded plots developed the highest pod numbers (58 pods), and the pod numbers were not influenced by nutrition treatments. Meanwhile, the grain yield also was not significantly different between nutrition treatments. However, soybeans treated with 200 kg N/ha yielded higher than the control (0 kg N/ha), with yields of 39.42 g/m^2 and 33.95 g/m^2, respectively. Previous studies have shown that soybean yields respond differently to nitrogen (N) nutrition, with some showing a positive response and others showing a negative response. The success of N application on soybeans is highly dependent on the variety and cultivation location. The positive response to N fertilizer may be due to a low-nodulation variety or environmental limitations on soybean growth. Both of these factors have restricted N fixation, resulting in a positive response to N fertilizer.

The study also found that soybean grain yields varied significantly depending on the weed canopy treatment. The hand weeded soybean yield was 51.52 g/m^2, significantly higher than the weedy (29.69 g/m^2) and mechanically weeded (28.32 g/m^2). However, the weedy canopy yield did not differ significantly from the mechanically weeded yield. Previous studies also showed that weeds interfere with the yield of soybeans. In fact, mechanical weeding, where the stump or root of the weed is still left in the ground, also interferes with the soybean yield. Therefore, one of the possible reasons behind the drop in yield is competition between crops and weeds for sources of nutrients, water, and light.

3.1.2 Chemical composition

The study found that nitrogen (N) supply did not significantly affect protein content, but there was a significant effect under weed canopy treatments. Mechanically weeded plants had the highest score (47.31%). Meanwhile, there were no significant differences in lipid content for both N and weed canopy treatments. Previous studies reported similar results for the response of protein, oil, or lipid content to N fertilizer. Varieties selection with desired oil and protein contents is a reliable method for producing premium soybeans. However, some studies found that N supply reduced protein and increased oil content compared to unfertilized soybeans. Soybean chemical compositions show inconsistent responses to N fertilization, possibly due to climatic conditions like lower temperatures and higher precipitation during seed filling.

There were also no significant differences in protein yields under different N supplies. However, applying 200 kg N/ha resulted in a higher protein yield compared to the control. The results of weed canopy treatments revealed that protein (23.35g/m^2) and lipid yields (6.51 g/m^2) under the hand weeded treatments were the highest. The high grain yield for hand weeded treatments led to higher protein and lipid yields than other treatments. Soybean production based on the yield of its chemical composition is important for the production of processed food products and oils.

3.2 Experimental Research 2: Influence of temperature and varieties on seed germination of soybeans at different germination times

3.2.1 Germination rate (%)

The germination rate of soybeans was significantly influenced by the day after sowing, temperature, variety, and temperature x variety. Both tested varieties showed an increase in germination rate from Day 3 to Day 9 (69% to 82%). The germination rate on Day 3 was significantly different from Days 5, 7, and 9. However, Days 5, 7, and 9 were not significantly different. Therefore, both varieties completed germination as early as the fifth day. The Martina variety had a higher germination rate (85%) compared to the Johanna variety (70%). Species that germinate earlier than other species can benefit from early access to resources and space, resulting in reduced competition. For the interaction effect between temperature and variety, the Martina variety achieved 100% germination at 15 °C and 96% at 25 °C, while the Johanna variety had a lower percentage of 74% at 15 °C and 76% at 25 °C. Previous studies showed that soybean seed responses vary greatly based on temperature, but some varieties respond well to low temperatures. Germination decreased dramatically when exposed to high temperatures (35 °C) in this study, with Martina achieving 61% and Johanna achieving 58%. High temperatures also resulted in seed germination performances dropping and being lower in most studies.

Most research, including ours, found that temperatures influenced most of the germination of plant varieties. When exposed to a certain temperature, the seed may react in the formation of the chemical composition, subsequently affecting germination. Most varieties have their own particular characteristics and differ from one another in terms of physical and chemical composition. In oilseed plants, such as soybean varieties that contain low lipids, the germination process is slow. This confirmed our findings that the Johanna variety showed a low percentage of germination at all tested temperatures (15, 25, and 35 °C). This is probably because the lipid content of the Johanna variety was lower than the Martina variety.

3.2.2 Total seedling length (cm)

Total seedling length is one of the indicators used to determine seedling vigour. Seedling vigour is defined as a seed's ability to emerge rapidly from soil or water, mainly referring to early seedling growth. The ANOVA showed that all main and interaction effects gave significant results. The total seedling length increased until Day 9 for both varieties when exposed to temperatures of 15 °C and 25 °C. The longest total seedling length was detected at a temperature of 25 °C, which was 10.83 cm (Martina) and 6.55 cm (Johanna). Therefore, both of the tested soybean varieties showed good seedling vigour because they can survive at a critical stage of early plant growth when exposed to low (15 °C) and optimal temperatures (25 °C). However, both varieties were more vigorous at 25 °C than at 15 °C because they had a longer seedling length at all germination periods. Based on previous studies, although soybeans can also easily germinate at low temperatures (10 °C), germination is slow.

However, the total seedling length increased only until Day 7 for both varieties when exposed to a high temperature of 35 °C. The total seedling length at a temperature of 35 °C was also the shortest for both varieties compared to the length at temperatures of 15 °C and 25 °C. On Day 9, the total seedling length at the temperature of 35 °C was only 2.63 cm for Martina and 1.58 cm for Johanna. This is most likely due to the drying of seedlings, which may be caused by conformational changes and hence the molecular deterioration of biochemicals within seeds under high temperatures and varying times. Overall, the Martina variety showed a longer total seedling length on varying days (3, 5, 7, 9) and at all temperatures compared to the Johanna variety.

3.2.3 Viability (%)

The viability results revealed that the main effects of temperature and variety had a significant effect. However, the percentage of viability for both varieties was not significantly different at temperatures of 15 °C (96%) and 25 °C (88%). The percentage of viability at those two temperatures was significant, as was the percentage of viability at a high temperature of 35 °C. At 35 °C, no seeds were viable (0%). Although some seeds germinated, the germinated seeds only survived until Day 7 and then died. Variety also had a significant effect on viability. The Martina variety (65%) performed better and was more viable than the Johanna variety (57%). Viability refers to whether a seed is alive or not, and the percentage of viable seeds is not necessarily the same as the percentage of germinated seeds. This difference is probably because some seeds are immature or dormant. The results of numerous publications confirmed that a temperature of 25 °C is the most beneficial for the germination of thermophilic plant species such as soybeans. The ideal germination temperature is an important factor that influences good further plant development, and seed viability is one of the indications used to evaluate further plant growth.

3.3 Experimental Research 3: Response of growth, yield, and chemical composition to nutrient concentrations of soybean varieties grown using a soilless culture system in a controlled environment

3.3.1 Plant growth

The study found that the main effects of the week and the interaction between nutrient concentration and variety significantly affected plant height. Plant height increased significantly every week until the fifth week (39.25 cm). It can be explained that every plant in excellent condition will continue to grow with increasing time. The plant is the most actively growing in the vegetative stage. The interaction effect showed that Martina was higher than Johanna when no nutrient was applied. When nutrients were applied up to 150%, the Johanna variety (35.88 cm) was higher compared to Martina (33.86 cm). This clearly shows that the determination of the nutrient concentration for a plant does not only depend on the type of plant but also needs to consider the variety used because each variety has a different response to nutrients.

The plants treated without nutrients (0%) and with 50% nutrients were not significantly different in the number of leaves. This is probably due to the large size of soybean seeds and the storage compounds in cotyledons that provide the necessary nutrients for early plant growth. This can explain why soybeans with 0% nutrients can also produce the same number of leaves as those with 50% nutrients, even if no nutrients are supplied. The effect of variety on the number of soybean leaves showed that both Martina and Johanna had a significant difference. The Johanna variety had more leaves than the Martina variety, which had 9 and 8 leaves. There was also a significant interaction between variety and week on the number of leaves. The number of leaves for both varieties increased with an increasing number of weeks. As explained earlier, the growth of a plant in the early stages, including the formation of leaves, will increase with increasing time. In Week 1, the number of leaves for the Johanna variety was higher than that for Martina. The number of leaves for the Martina variety then increased in Week 5 and reached a higher level than the Johanna variety.

The study found no significant differences in the main effect of nutrient concentration and variety on SPAD reading. However, the main effect of week number and the interaction between variety and week number were significant. The Johanna variety had a higher SPAD reading than the Martina variety in Weeks 1, 2, and 3, with a maximum reading of 38.65 and 38.21. The Johanna variety decreased drastically and had a lower SPAD reading compared to the Martina variety in Weeks 4 and 5. The SPAD reading, which measures leaf green colour intensity, is related to chlorophyll content in leaves and stems, which plants use to produce food through photosynthesis. The Johanna variety had a high photosynthesis rate in the early stages of growth and decreased in the last two weeks of its vegetative stage, while the Martina variety was more productive in producing food during the two weeks before its vegetative stage ended.

Meanwhile, the results on leaf area showed that nutrient treatments increased leaf size significantly with increasing concentration, with the largest being at 150% concentration (37.40 cm^2). Since plants at higher nutrient concentrations allocate a larger fraction of carbohydrates to shoot growth than those at lower concentrations, plants at high nutrient concentrations could produce a wider leaf area. The Martina variety had a larger leaf area than the Johanna variety, with 36.66 cm^2 and 31.05 cm^2, respectively. The week also had a significant effect on leaf area, with an increase from Week 1 until Week 3 and a slight decrease in Week 4. However, the leaf area in Week 4 was not significantly different from Week 3, and the leaf area continued to decrease in Week 5 without a significant difference between Week 4 and Week 2.

There was a significant interaction effect between nutrient concentration and variety on root length. The study found that the Martina variety had deeper roots than the Johanna variety at 0% nutrient concentration, with lengths of 12.56 cm and 10.22 cm, respectively. At a nutrient concentration of 50%, the Johanna variety had deeper roots than the Martina variety. The highest root lengths were observed in this treatment, with 16.48 cm for Johanna and 15.61 cm for Martina. Similar results were obtained at 100% and 150% concentrations, with the Johanna variety having deeper roots than the Martina variety. However, the root length of both varieties increased as the nutrient concentration treatments increased from 0 to 50%. When the nutrient was increased to 100%, the root length of both varieties was shorter but not significant. The findings of this study suggest deeper roots in plants with low nutrient supplies. Based on a previous study, there was an increase in the elongation of vertical or deep roots for various plants grown in soilless culture systems when there was a limited nitrogen supply. It is due to the root's nature, which functions as a vital organ providing physical anchoring, nutrient absorption, water, stress prevention mechanisms, and signals to the aerial part of the plant.

Another plant growth parameter was the shoot:root ratio. The shoot:root ratio in plants significantly varies with nutrient concentration and variety treatment. The ratio increases with nutrient concentration from 0 to 150%, while a nutrient-free treatment has the lowest ratio. This ratio is typically increased with fertilizer concentration, and deficiencies in water or nutrients can decrease it. The Martina variety had a higher shoot:root ratio than the Johanna variety. A high ratio indicates a greater proportion of shoots compared to roots, allowing plants to capture light energy and grow larger.

3.3.2 Yield formation

The results showed that the nutrient and variety treatments significantly affected the number of pods/plants. The number of pods/plants for soybeans with a 150% nutrient concentration was the highest, followed by 100%, 50%, and 0%. The result also revealed that the Johanna variety had more pods/plants than the Martina variety. The study also found that the 100-grain weight was significantly influenced by nutrient concentration and variety. Treatment with 100% concentration gave the highest value of 100-grain weight, but it was not significant with 100-grain weight at 150% treatment. The Johanna variety had a significantly higher 100-grain weight than the Martina variety. This is an essential agronomical characteristic, as genes related to it are targeted to enhance soybean grain quality. The Johanna variety had a higher 100-grain weight and a more prominent grain size than the Martina variety, supporting the results of the study.

The other finding was the grain yield/pot. The study found that grain yield/pot significantly varies depending on the nutrient concentration treatment. The lowest yield was observed for soybeans with 0% (3.93 g) and continued to increase until 150% nutrient concentration (30.66 g). This increase may be due to the greater nutrient uptake of the crop, which affects growth and yield components that effectively assimilated the partitioning of photosynthesis from source to sink in the post-flowering stage and resulted in the highest grain yield. Martina and Johanna varieties yielded comparable results, with 16.38 g and 17.07 g, respectively.

3.3.3 Chemical composition

The result showed that both tested factors interacted significantly on protein content. The Johanna variety had higher protein content than the Martina variety at different nutrient concentrations. At a 50% nutrient concentration, both varieties had the highest protein content, which was 46.59% (Johanna) and 46.15% (Martina), but decreased by 3.49% (Johanna) and 3.70% (Martina) when supplied at 100%. At a 150% nutrient concentration, Johanna's protein content was 1.81% higher than the 100% treatment. However, the protein content of Martina was almost the same as the 100% treatment (42.47% and 42.45%). The Johanna variety had a higher protein content, which may be due to its larger size, as large soybean grains can produce more protein.

The study also found significant interaction effects on lipid content. Martina and Johanna varieties had higher lipid content in the 0% nutrient treatment, with Martina having 14.27% and Johanna having 13.67%. The lipid content increased at 50% nutrient concentration but had the lowest value compared to other treatments. At 100% nutrient concentration, lipid content increased again, but Martina had a higher lipid content (14.98%) than Johanna (13.84%). The response to lipid content differed from protein content, possibly because smaller varieties usually have a higher lipid content. Soybeans with greater protein content also had lower lipid contents, resulting from the pleiotropic effects of minor and major genes related to protein and lipid content. Protein and lipid content strongly influence each other in soybean plants, which are influenced not only by the environment or meteorological conditions but also by nutrient management and variety.

Our findings also revealed that only nutrient concentration significantly impacts protein and lipid yield. The study found that protein yield increased from 0 (1.73 g) to 150% (13.43 g) nutrient concentration, and lipid yield also increased from 0 (0.55 g) to 150% (13.43 g). Although protein yield was higher at 50% nutrient concentration, low grain yield caused low protein yield. Protein and lipid yield are crucial in soybean production, especially for producing soybean-based secondary products for human or livestock consumption. This is because they consider the total nutritional value of soybean crops.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The performance of the soybean variety ES Gladiator grown in the open field revealed that it was not influenced by nitrogen (N) nutrition but was strongly influenced by the weed canopy. The presented outcomes in Experimental Research 1 suggest that the variety which was cultivated in black forest soil did not require additional N supplies from mineral fertilizer since all the recorded parameters were not statistically significant. The results on the influence of weed canopy can be concluded that weed canopy under hand weeded had a positive effect on grain, protein, and lipid yields, with all these parameters measured being the highest and almost doubled compared to control (weedy). However, the weed canopy under hand weeded treatment was not significant compared to the control in affecting protein and lipid content. For all treatments, the protein content had the opposite effect as the lipid content.

Meanwhile, the performance of the soybean varieties Martina and Johanna at the germination stage, which was 12 days after planting in a controlled environment, as presented through outcomes in Experimental Research 2 showed that the Martina variety was significantly higher than the Johanna variety on germination rate, seed vigour, and seed viability. However, variety interacted with temperature in influencing germination rate. Both varieties have comparable germination rates at temperatures of 15 °C and 25 °C and were higher compared to the germination rate at high temperatures (35 °C). Variety also interacted with temperature and germination period (days) in influencing the total seedling length. The longest total seedling length was found in the Martina variety at a temperature of 25 °C on the ninth day. Both varieties were more viable at low temperatures (15 °C) and suboptimal temperatures (25 °C), while none survived at high temperatures (35 °C). Therefore, both of these soybean varieties were also tolerant to the low temperatures.

In Experimental Research 3, the Martina and Johanna varieties, grown in a controlled environment using the soilless substrate of expanded clay aggregate, showed good vegetative growth. The nutrient solution of Advance Hydroponics of Holland at different rates influenced plant growth, including plant height, leaf number, and leaf area. The Johanna varieties produced more leaves and higher chlorophyll content, while Martina had larger leaf sizes. Both varieties required additional nutrients between 100% and 150% for optimal early growth. Meanwhile, the effects of different nutrient solutions on shoot and root growth, grain yield, and chemical composition of the Martina and Johanna varieties were that the application of nutrient concentration at 50% produced the deepest root and the highest protein content for both varieties. However, the application of 100% nutrient concentration gave a higher 100-grain weight for the Johanna variety. The application of nutrient concentration at 150% was good for shoot growth since it gave the highest shoot weight and shoot:root ratio for both varieties, with Martina being higher than Johanna. At 150% nutrient concentration, it also produced the highest number of pods for the Johanna variety and the highest grain yield for both varieties. Meanwhile, the Martina variety had the greatest lipid content at 150% concentration. Protein and lipid yields were also higher for both varieties at a nutrient concentration of 150%.

Therefore, it can be concluded that the use of nutrient concentrations of Advance Hydroponics of Holland (Dutch Formula) between 100% and 150% gave a positive effect. It can be used for planting Martina and Johanna varieties in a controlled environment using an expanded clay aggregate substrate. This is based on this cultivation technique that produced a high 100-grain weight and grain yield as well as high protein and lipid yields for both varieties.

Thus, all the information obtained from all three experimental studies will indirectly contribute to the determination of the appropriate practices for the cultivation of soybeans using the ES Gladiator variety for field conditions and the Martina and Johanna varieties for controlled environment conditions. These findings also provide specific information for the development of new planting technologies for these varieties in both cultivation systems.

4.2 Recommendations for future research

Based on the findings of this study, some recommendations for future research are as follows:

- ✧ This study examined the effect of nitrogen fertilizer on the ES Gladiator soybean variety grown in a field. Therefore, it is suggested for future research investigate the effects of other macronutrient elements such as phosphorus (P) and potassium (K) on this variety in the same soil type so that a complete NPK fertilizer recommendation can be made.
- ✧ This study also investigated the influence of temperature on the early stages of growth, including germination and seedling development of the soybean varieties Martina and Johanna. Thus, other factors that influence the growth of this soybean variety, such as water requirements, can be investigated, as water requirements are crucial, particularly in the early stages of plant growth.
- ✧ The effect of nutrient concentration in a controlled environment was tested on Martina and Johanna varieties, and the appropriate rate can also be recommended. However, further research on other crucial agronomic practices, such as the requirements for light, water, and different types of soilless substrates, can also be done to boost the yield and chemical composition of soybeans.
- ✧ This study examined the effect of variety, nutrient requirements, and weed control on the growth, yield, and nutritional composition (protein and lipid content) of soybeans. It is also possible to investigate the effect of these factors on biochemical content or secondary metabolites such as isoflavones, which function as antioxidants and anti-inflammatory agents.

5. NEW SCIENTIFIC RESULTS

1. This study proved that the use of nitrogen fertilizer at an amount of 200 kg N/ha did not have a positive effect on the number of pods, grain yield, protein content, protein yield, and lipid yield of ES Gladiator varieties grown in black forest soil.
2. The weed canopy under hand weeded treatment had the highest grain, protein, and lipid yields and almost doubled compared to the control (weedy), but was not significant compared to the control in affecting the protein and lipid content of the ES Gladiator variety.
3. The germination study revealed that the Martina variety outperformed Johanna in germination rate, seed vigour, and viability. Both varieties had high germination rates at 15 °C and 25 °C, with the Martina variety having the longest total seedling length at a temperature of 25 °C on the ninth day.
4. The study in a controlled environment using a soilless substrate of expanded clay aggregate revealed that the Martina variety had the highest plant height at 0% and 100% nutrient concentrations, while the Johanna variety had the lowest height. Martina leaves were larger, but Johanna produced more leaves and had a higher chlorophyll content.
5. The study in a controlled environment also revealed that the SPAD reading for both Martina and Johanna varieties increased until Week 3 (30 days after planting), decreased at Week 4, and was maintained at Week 5.
6. The use of a 50% nutrient concentration of Advance Hydroponics of Holland in a controlled environment using a soilless substrate of clay mineral aggregate produced the deepest root and the highest protein content for both the Martina and Johanna varieties.
7. The use of nutrient concentrations of Advance Hydroponics of Holland between 100 and 150% gave a positive effect for both the Johanna and Martina varieties planted in a controlled environment based on high pod number, better 100-grain weight and grain yield per pot, high lipid content, as well as high protein and lipid yields per pot.

6. PUBLICATIONS

6.1 List of publications related to the topic of the dissertation

1. Abd Ghani, R., Omar, S., Jolánkai, M., Tarnawa, Á., Khalid, N., Kassai, M.K., & Kende, Z., (2023). Response of shoot and root growth, yield and chemical composition to nutrient concentrations in soybean varieties grown under soilless and controlled environment conditions. *Agriculture*, 13(10), 1925. IF: 3.6. https://doi.org/10.3390/agriculture13101925
2. Abd Ghani, R., Omar, S., Jolánkai, M., Tarnawa, Á., Kende, Z., Khalid, N., Gyuricza, C., & Kassai., M.K. (2023). Soilless culture applications for early development of soybean crop (*Glycine max* L. Merr). *Agriculture*, 13(9), 1713. IF: 3.6. https://doi.org/10.3390/agriculture13091713
3. Abd Ghani, R., Jolánkai, M., Omar, S., Khalid, N., & Tarnawa, Á. (2023). Influence of temperature and variety on seeds germination and seedlings emergence of soybean (*Glycine max* L. Merr) at different germination times. *Acta Agraria Debreceniensis*. 2023(2). https://doi.org/10.34101/actaagrar/2/13171
4. Abd Ghani, R., Kende, Z., Tarnawa, Á., Omar, S., Kassai, M.K., Jolánkai, M., & Khalid, N. (2023). Nitrogen nutrition and weed management effects on yield and chemical composition of soybean (*Glycine max* L. Merr). *Proceeding of The Youth Science Forum,* 8 June 2023, Keszthely, Hungary, 241-246.
5. Abd Ghani, R., Kende, Z., Tarnawa, Á. Omar, S., Kassai, M.K., & Jolánkai, M. (2021).The effect of nitrogen application and various means of weed control on grain yield, protein and lipid content in soybean cultivation. *Acta Alimentaria*, 50(4), 527-547. IF: 1.2. http://doi.org/10.1556/066.2021.00095
6. Abd Ghani, R., Omar, S., EL Chami, E., EL Chami, J., & Jolánkai, M. (2021). Agri-environment impacts on yield formation of soybean crop. *Columella*, 8 (2), 5-10. https://doi.org/10.18380/SZIE.COLUM.2021.8.2.5

6.2 List of publications not related to the topic of the dissertation

1. Omar, S., Abd Ghani, R., Khalid, N., Jolánkai, M., Tarnawa, Á., Percze, A., Mikó, P.P., & Kende, Z. (2023). Effects of seed quality and hybrid type on maize germination and yield in Hungary. *Agriculture*, 13(9), 1836. IF: 3.6. https://doi.org/10.3390/agriculture13091836

2. Khalid, N., Tarnawa, Á., Balla, I., Omar, S., Abd Ghani, R., Jolánkai, M., & Kende, Z. (2023). Combination effect of temperature and salinity stress on germination of different maize (*Zea mays* L.) varieties. *Agriculture*, 13(10), 1932. IF: 3.6. https://doi.org/10.3390/agriculture13101932
3. Omar, S., Abd Ghani, R., Tarnawa, Á., Kende, Z., Kassai, M.K., & Jolánkai, M. (2023). Impact of N Supply on Some Leaf Characteristics of Maize Crop. *Columella,* 10(1), 15-25. https://doi.org/10.18380/SZIE.COLUM.2023.10.1.15
4. Omar, S., Abd Ghani, R., Khalid, N., & Jolánkai, M. (2023). Evaluation of maize inbred lines and hybrids for agronomic characteristics, yield and grain quality. Proceeding of The *Youth Science Forum,* 8 June 2023, Keszthely, Hungary, 253-258.
5. Omar, S., Abd Ghani, R., Khaeim, H., Sghaier, A.H., & Jolánkai, M. (2022). The effect of N fertilization on yield and quality of maize (*Zea may* L.). *Acta Alimentaria*. 51(2), 249–258. IF: 1.2. https://doi.org/10.1556/066.2022.00022
6. Omar, S., Tarnawa, Á., Kende, Z., Abd Ghani, R., Kassai, M.K., & Jolánkai, M. (2022). Germination Characteristics of Different Maize Inbred Hybrids and Their Parental Lines. *Cereal Research Communication,* 50, 1229–1236. IF: 1.24. https://doi.org/10.1007/s42976-022-00250-9

6.3 List of conducted conference presentation

1. Abd Ghani, R., Kende, Z., Tarnawa, Á., Omar, S., Kassai, M.K., Jolánkai, M., & Khalid, N. (2023). Nitrogen nutrition and weed management effects on yield and chemical composition of soybean (*Glycine max* L. Merr). Oral presented in *Youth Science Forum,* 8 June 2023, Keszthely, Hungary.
2. Omar, S., Abd Ghani, R., Khalid, N., & Jolánkai, M. (2023). Evaluation of maize inbred lines and hybrids for agronomic characteristics, yield, and grain quality. Oral presented in *Youth Science Forum,* 8 June 2023, Keszthely, Hungary.
3. Jolánkai, M., Abd Ghani, R., Omar, S., Kende, Z., Kassai, M.K., & Tarnawa, Á. (2021). Water footprint of protein yield of field crop species based on evapotranspiration patterns. Oral presented in *First National Interdisciplinary Climate Change Conference* (HUPCC), Online conference. 12 - 15 April 2021.