DEVELOPMENT OF AGRICULTURAL MACHINERY WITH DEEP PLACEMENT FERTILIZER TECHNOLOGY TO ENHANCE CROP PRODUCTION IN THE FAR EAST OF RUSSIA

Ph.D. Dissertation

by

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Abbreviations

PK: Primorsky Krai

DPFT: Deep placement fertilizer technology

DPFA: Deep placement fertilizer applicator

FEM: Finite element method

SF: Safety factor

AV: Average

AIC: Agro-industrial complex

PSAA: Primorskaya State Academy of Agriculture

ETI: Engineering and Technology Institute

MAFF: Ministry of Agriculture, Forestry and Fisheries

CIS: Commonwealth of Independent States

SICR: Strategic international collaborative research

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ABSTRACT

Nowadays, the agricultural sector has become flexible and changeable in order to supply sufficient and pure food for the population. Therefore, scientists with the cooperation of farmers in many developing countries are looking for new technologies to increase crop yields and incomes, reduce the amount of fertilizer used, reducing labor, and also decreasing environmental damage to the atmosphere and water. These issues play a crucial role in the sustainable development of advanced agriculture.

This Ph.D. research, at first, overviewed the economic sector focused on agricultural production and the current agricultural machinery market in Primorsky Krai (PK), Far East of Russia. The research also briefly analyzed PK research and development activities for agricultural machinery. It was found that many enterprises currently prefer to focus on reliability and low cost agricultural machinery to achieve better production, which plays a key role in PK agricultural development.

Secondly, the Ph.D. study has investigated the practicability of a developed conventional Russian manufactured seeder for soybean sowing by using a deep placement fertilizer technology (DPFT), toward enhancing potential crop production in PK. Moreover, the development of deep placement fertilizer applicators (DPFA) has been considered in this study as one of the most important issues in developing combined subsoil tools for saving labor in using new agricultural machinery and Agro-technology. Thus, this study is focused on a methodological system with multiple laboratories and practical field experiments. Advanced equipment and methods such as finite element method (FEM) simulation with the use of additional strain gage pieces of equipment have been used for the practical approach.

The study result indicates the practical use of the developed seeder and DPFA, findings on soil dynamic resistance induced on the DPFA, the results of soybean growth and development by the DPFT, and provides further research recommendations. Moreover, the current study results provide fundamental and practical support for the development of agricultural machinery, specific and conventional tools, especially for DPFA, which will be useful for further research on the development of the DPFT in the Far East of Russia.

CHAPTER 1

INTRODUCTION

The quick development of all Russian agriculture has become a well-known fact in recent years. The Ministry of Agriculture of Russia has reported that one of the most productive years of the agricultural industry was 2017, because of the governmental support which has been started in several state programs for crop production and greenhouse industries (Ministry of Agriculture of Russia, 2018). Furthermore, one of the most important aims was to improve existing agricultural productivity by promoting new technical and scientific methods, which positively affect the level of productive efficiency. Therefore, developing conventional agricultural practices that are already used in Russian agriculture, such as soil cultivation techniques, mechanization tools, agricultural machinery, and other issues, may be a critical factor in improving agriculture in general.

For Russian Far East agriculture, soybean has one of the most critical values in crop production. The value of soybean is determined by the uniqueness of the biochemical composition of its seeds, containing on average 20% of fat and 40% of protein. Moreover, soy protein is highly valuable, as it contains a high nutritional value and all the amino acids necessary for humans and animals. For instance, the lysine (lysin) essential amino acid content in soy flour is 8 – 9 times higher than in wheat, and two times higher than in beef (Mohsen et al., 2009). Therefore, great research and practical interests are the design of new practical-friendly agricultural machinery and the implementation of new fertilizer application technologies such as a deep placement fertilizer technology (DPFT), to enhance soybean quality and yield potentiality.

This Ph.D. study was conducted within a joint international research project on soybean production between Primorskaya State Academy of Agriculture (PSAA), Russia, and Niigata University, Japan by a pilot project for the development of Strategic International Collaborative Research (SICR) in the field of agriculture under the auspices of the Ministry of Agriculture, Forestry and Fisheries (MAFF), Japan.

The purpose of the Ph.D. study is to investigate the practicability of a developed Russian manufactured seeder by using DPFT, toward enhancing potential crop production in Primorsky Krai (PK), Far East of Russia. The fundamental purpose of this study is to achieve a cost-effective model on the country’s market, which could be equivalent to more expensive competitors on the global machinery market, and meeting high-performance characteristics of those other seeders during the seeding performance. Moreover, the development of deep placement fertilizer applicators (DPFA) has been considered in this study as one of the most important issues in developing subsoil tools in new agricultural machinery and Agro-technology. Thus, this study is focused on the methodological approach with a range of multiple laboratories and practical field experiments, and their obtained results. Laboratories and field experiments were done in order to clarify and evaluate the practicability of a developed Russian manufactured seeder by DPFT, as well as developed DPFAs in subsoil performance, and soybean plant development on the side of PK.

Consequently, the purpose of Chapter 2 is to overview the status of agriculture and agricultural mechanization in PK, including the overall status of the agricultural machinery market. Further, the purpose of Chapter 3 is to describe issues, background study, proposed hypotheses, the purpose of the development of agricultural machinery by using DPFT, and used methodology to approach the study aims. Finally, Chapter 4 represents the main value of this study by providing practical applied knowledge of the obtained results, including theoretical and technical support for agricultural machinery and the development of tools. Furthermore, Chapter 5 is representing a summary and conclusions along with further research prospects to assess the long-term utilization and impact of DPFT on soybean cultivation in Russian agriculture.

CHAPTER 2

CURRENT STATUS OF AGRICULTURE AND AGRICULTURAL MECHANIZATION IN PRIMORSKY KRAI

2.1 Introduction

Primorsky Krai (PK) is a federal district of the Russian Federation. It is part of the Far Eastern Federal District and located in the far southeastern part of the country. PK lies on the western coasts of the Sea of Japan. It shares borders with Khabarovsk Krai in the north, China in the west, and North Korea in the southwest. The PK land area is 165,900 km^2 (Fig. 1).

Figure 1. Location of Primorsky Krai

Currently, PK is becoming a more economically active region owing to the development of foreign agriculture in the Far East. Over the past couple of decades, neighboring countries have been rapidly increasing their investments in PK. The agro-industrial complex (AIC) of PK is one of the most important agricultural producers in Russia. It primarily grows agricultural crops, such as rice, soybeans, wheat, corn, and vegetables, and raises livestock and poultry. The PK AIC is in a favorable position for mutually beneficial agriculture agreements between neighboring countries.

Therefore, due to its geographical location (close to China), suitable climate, landform, and facilities for rice farming in PK, there are many Chinese investors involved in rice production

(Zhou, 2018). Plus, the Ministry of Agriculture, Forestry and Fisheries (MAFF) Japan has a current interest in the agricultural development of the Russian Far East region, under established objectives of Global Food Value Chain Strategy (GFVCS). One of the main GFVCS objectives is to promote the economic growth of developing countries and promote cooperation on food value chain from farmers to consumers by cooperating between state (public) and private sectors, and with the official economic cooperations and investments by the Japanese food industry. In addition, MAFF has set up a platform by the Japanese government in order to support Japanese companies interested in agriculture, forestry and fisheries, and related businesses in the Russian Far East region (MAFF, 2018).

Besides, many studies have examined agricultural production, regional investments, and land conditions in the Far East. Several studies have been made on Japanese investment in PK (Ershova, 2014), development of rice yield in PK (Pestereva, 2014), soybean production (Park et al., 2015), education for the development of the AIC (Komin et al., 2017), and Chinese agriculture in PK (Zhou, 2018). However, the current status of agricultural mechanization has not yet been studied. Thus, the overview of the status was an essential topic to conduct this study on the occasion of future perspectives of agricultural mechanization in PK.

2.2 Agricultural production in PK

PK is a quickly growing region with the most balanced economy in the Russian Far East. The foundation of the region's economy is the richness of its natural land and ocean resources. The industrial complex is the most developed part of the PK economy. The main industrial complex comprises agriculture, fishing and fish processing industries, electric power and coal extraction industries, engineering and ship repair industries, and timber and woodworking industries.

Agricultural production is one of the most important sectors in PK, and it has a wide product range. It plays an important place in the Russian Federation due to its large land resources, grain and leguminous crops production, vegetable production, and livestock production. Despite these advantages, it cannot be said that PK has entirely realized its full potential in agriculture or any other industry.

Agricultural production in PK is mainly located in the southern and southwestern districts, although agriculture is present throughout the region. Figure 2 shows the locations of agricultural production districts.

Figure 2. PK districts with large agricultural production

1 – Khankaysky; 2 -Spassky; 3 – Pogranichny; 4 – Khorolsky; 5 – Chernigovsky; 6 – Oktyabrsky; 7 – Mikhaylovsky; 8 – Ussuriysky Urban District; 9 – Nadezhdinsky; 10 – Artem Urban District

The PK produces grain and leguminous crops, such as soybean, potatoes, spring wheat, oats, corn, beans, and rice, in addition to different types of vegetables. Figure 3 shows the gross production and cultivated area of main crops and vegetables in farms for all agricultural categories (Agricultural enterprises, Peasant farm enterprises, and Individual entrepreneurs). In addition, the gross production and cultivated area of soybean is shown separately in Fig. 4, since the soybean production has the main focus in the study.

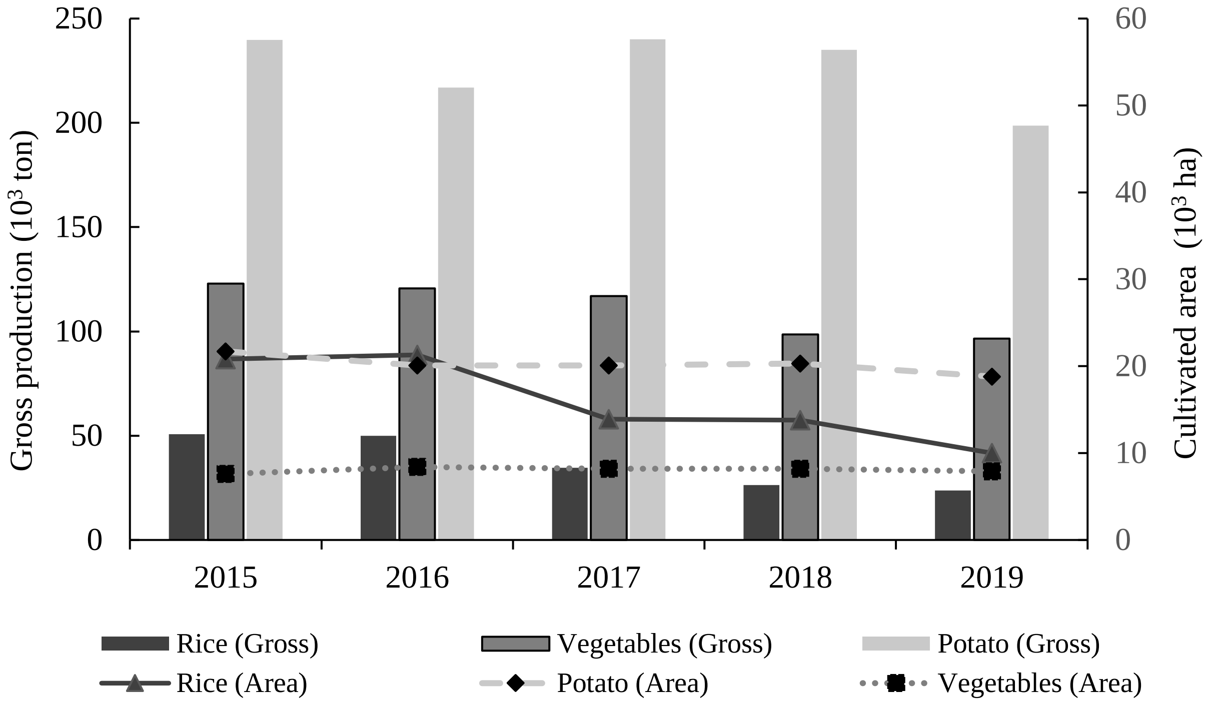


Figure 3. Main gross production and cultivated area in PK

Sources: Primstat, 2020; Department of Agriculture and Food of Primorye Territory, 2018.

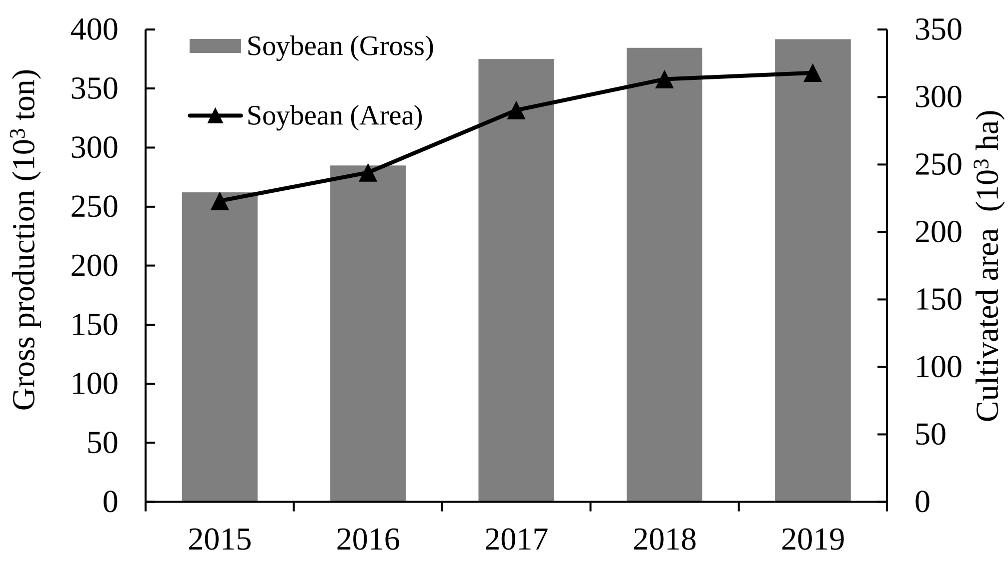


Figure 4. Soybean gross production and cultivated area in PK

Note: Average Yield – 1.3 t/ha (2015-2019)

Sources: Primstat, 2020; Department of Agriculture and Food of Primorye Territory, 2018.

Soybean production has the most significant production quantity compared to other produced crops. Moreover, it has a positive trend in increasing production and cultivated areas every year. However, the average soybean yield remains similar quantity (1.3 t/ha) during recent years, and in comparison, to a country with a large scale of agriculture and developed soybean production (e.g. the U.S.) this soybean yield remains low. According to the U.S. Department of Agriculture, in 2018 the average soybean yield was 3.5 t/ha (51.6 bushels per acre (bsh/ac)), which is 2.5 times more than in PK (USDA, 2020). Besides, in the U.S. the soybean yields ranged from less than 2.7 t/ha (40 bsh/ac) to greater than 4.4 t/ha (60 bsh/ac). Moreover, the soybean yield significantly depends on a soybean variety, and it is always important to develop and improve soybean varieties.

The formation of a high-performance agricultural sector in PK requires an appropriate level of development of the material and technical basis of agricultural enterprises. Thus, although mechanization is an important factor in enhancing farm productivity, and the priorities of most organization policies and programs focus on enhancing agricultural production,. However, mechanization has generally not been supported by the programs with respect to smaller production systems, that is, peasant and individual enterprises (Kienzle et al., 2013).

2.3 Agricultural mechanization and agricultural machinery market

2.3.1 Agricultural mechanization structure

In order to know the overall structure of agricultural machinery and equipment, the official data published by the Statistics Office of PK was used. The data published by the Statistics Office was not satisfactory, because they were not systematically collected every year. Hence, it was necessary to ask the office directly for the information needed to develop this study. In addition, due to the specific method of data collection in the Russian Federation and local statistics centers, unfortunately, statistical reports lack some needed data. The reports include all the tractors registered on the balance sheets of agricultural enterprises, which includes leased equipment, as well as machinery on the off-balance-sheet account. The reports do not indicate important technical details, such as tractor power, manufacturer names, and condition (e.g., under repair or broken but not yet written off). However, the statistical reports provide general official information about agricultural mechanization. Figure 5 illustrates the total numbers of the main agricultural equipment, and the average ratio (AR) between the number of tractors to the number of agricultural machinery, which was used and currently is used in PK. Moreover, a full account of the data is presented in Tab. 1 in App. 1.

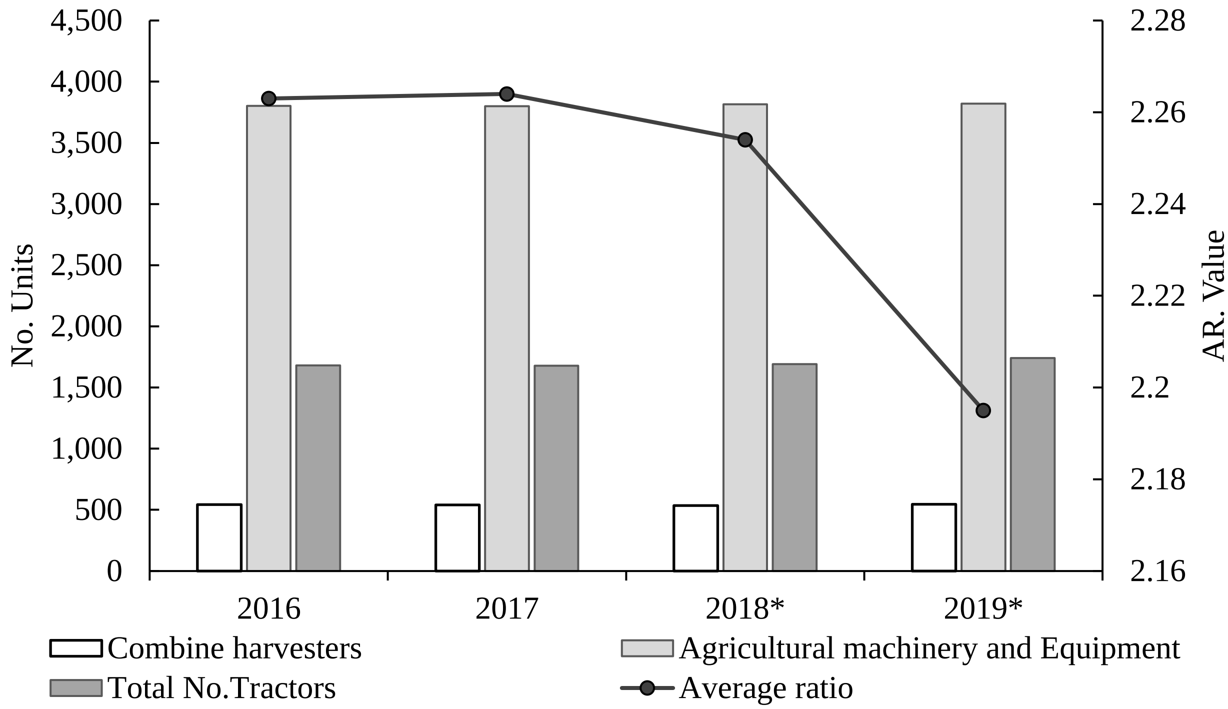


Figure 5. Total number of the main agricultural machinery use

Note: * – Data was collected by own observation

Sources: Primstat, 2020; Department of Agriculture and Food of Primorye Territory, 2018.

Equation 1 allows us to determine the AR between the number of tractors to the number of agricultural machines (eq. 1). This factor is one of the most important factors in calculating the energy input and output in terms of crop production in agriculture (Ozkan et al., 2004).

$$\frac{No.\ Agricultural\ machinery}{No.\ Tractors} = \mathrm{AR.\,Value} \quad (1)$$

This value can show the usage efficiency of all agricultural machinery and equipment per number of tractors, which is an important issue depending on the crop seasons (e.g. pre-sowing activities (fall and spring tillage), sowing and harvesting seasons). For instance, the best usage efficiency of a number of agricultural machines to a number of tractors will show the equal value as a coefficient one (1), and it means with every single tractor there is one specific agricultural piece of equipment. However, it will lead to a higher cost of agriculture in general. By analyzing the AR from figure

5, we can notice that the AR value was decreased by putting new tractors in agricultural operation. Besides the fact that the number of agricultural machines and equipment was also increased, however, the total number of tractors continues to dominate. Furthermore, referring to figure 4 (Soybean production), positive dynamics can also be seen in terms of total productivity and an increase in the number of cultivated areas.

However, due to a lack of data (which was discussed above), it is not currently possible to clarify in detail the perspectives of agricultural mechanization, or obtain any sufficient correlation e.g. between soybean cultivation and specific tractor sizes (i.e. power, scale, etc.). Because it is necessary to know in which direction that both variables move. As an example, if soybean cultivation areas and yields increase, the number of tractors decreases proportionally, which will indicate the efficient use of tractors and soybean productivity. By the current data, it is possible to obtain base knowledge of the overall situation in PK.

2.3.2 Agricultural machinery market

The overall PK status of the agricultural machinery market was analyzed to classify it and identify opportunities for expansion. The overall analysis was based on the distribution from sales offices, data on import and export of agricultural equipment and machinery, details on warranty and post-warranty support, and the PK farm machine service network.

Structure of the agricultural machinery market

The PK agricultural machinery market can be divided into three categories. The first category contains machinery from official dealers of well-known international machinery brands, the second category is concerned with dealers of domestic brands of machinery, and the third category is a private market that consists only second-hand[1] machinery. The first two categories can be further subdivided into markets for new and used machinery. Figure 6 shows PK farm machinery market model.

[1] Machinery that was previously used by farmers

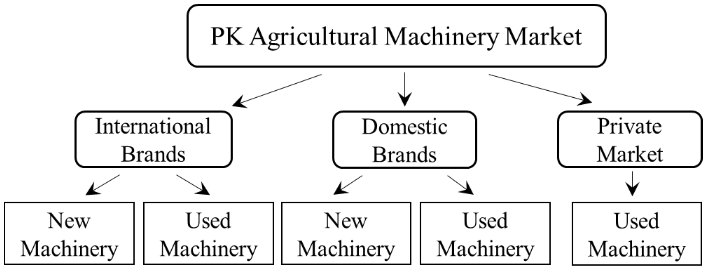


Figure 6. PK market model

In PK, several companies (limited liability companies) are official dealers of well-known machinery brands, including Russian and imported brands. Common brands (and country of origin) include the Rostselmash group (Russia); Gomselmash (Republic of Belarus); Claas, Lemken, and Amazone (Germany); Salford Group (Canada); Maschio Gaspardo and New Holland (Italy); and AGCO Corporation (Challenger, Fendt, Massey Ferguson, and Valtra brands), John Deere, and Case IH (USA). Figure 7 provides the names and locations of machinery dealers.

Figure 7. Location of official machinery distributors, 2018

1 – DalAgroLiga; 2 – East Gate ES; 3, 4, 6 – Siberian Service Company; 3, 5 – Tate Company

Note: Fast market expansion[2]

[2] Due to the fast market expansion, not all companies can be seen on this map (e.g. Rusagro Group)

All companies identified in Figure 7 provide new agricultural machinery and equipment, as well as second-hand machinery. Each company offers full lines of tractors, combine harvesters, hay and forage equipment, seeding and tillage implements, grain storage systems, and replacement parts for the above equipment. However, few of these companies stock the full line of agricultural machinery and equipment at their location. Generally, only 50–70% of the machines that are in demand are stocked on-site. When a distributor does not have an item of equipment in stock, it is ordered and delivered through the company's supply network in Russia or abroad.

After-sale and supplementary services, and used machinery

Each company in Figure 7 has its own after-sale service with different options. With the purchase of any equipment by a client, a company issues a service book that records all the data from previous diagnostic and maintenance services, as well as a dataset for the next scheduled maintenance appointment. Furthermore, the distributor typically tracks maintenance services and contacts the machinery owner to schedule an appointment.

Most companies have mobile teams for maintenance and diagnostic services to address equipment breakdowns. If the maintenance or repair service cannot be provided at the machinery location or the machine cannot be driven to a service facility on public roads, the company provides transportation to a repair facility. Moreover, several companies have a network in Russia for the fast delivery of replacement parts. Parts can reach a customer by plane, train, car, and other means in 1–4 days. This facilitates the rapid repair of agricultural machinery and equipment, which is especially important during harvest time.

The supplementary services of companies sometimes assist with machinery selection so the agricultural producer can maximize the machinery's potential. Due to different landscape terrains in PK, field sizes are both small and large (Starogilov, 2009), so companies will calculate machinery power and size for producer-specific fields. Several companies (e.g., Tate and Siberian Service Company) provide document preparation and execution services for purchase via leasing and provide other leasing assistance.

The used agricultural machinery and equipment, including international and domestic brands, are divided into two categories. The first category is under support of the selling company (e.g., warranty and warranty maintenance). The second category does not have any official support from the selling company.

An example of the first category is the *Tate company*, which is an official distributor of John Deere (USA) in PK. The company provides imported new and used agricultural machinery and equipment from the USA. Used machinery and equipment have a warranty period of 6 months, but the warranty is only for the engine and transmission mechanism. However, new machinery and equipment have a warranty period of 2–5 years, and the warranty covers all machinery malfunctions. The warranty period is determined by the machinery model and the sales agreement. Moreover, the company provides the warranty under specific conditions, which generally require the machinery owner to use only the company's diagnostic tools, maintenance, technical fluids, and replacement parts.

Private market

The private market allows agricultural producers to sell and buy any equipment that they or other agricultural producers used previously. This kind of market increases the machinery choices available to agricultural producers and lets them sell machinery or equipment that they do not use anymore or upgrade older equipment without incurring the expense of dealer-supplied equipment.

In PK, many types of agricultural machinery and equipment are available from bordering countries. According to information from one Russian vehicle market website (Drom.ru, 2020), agricultural machinery and equipment are available from primarily four countries in the private PK market, Japan, China, Russia and Commonwealth of Independent States (CIS) countries (Republic of Belarus and Ukraine). Furthermore, most tractors and agricultural equipment are imported from Japan and cover 70–85% of the private market, and figure 8 illustrates the number of tractors available in each power range graphically. Moreover, the details of the origins and brands of tractors available on (Drom.ru) private market during May 2020 are presented in Tab. 2 in App. 1.

From table 2 (App 1) shows that most of the private market tractors were made by Japanese manufacturers (332 tractors) and had a power range of 10–25 kW (230 tractors), although other tractor sizes were also available. Moreover, the second place of the private market is taken by Russia and CIS countries (102 tractors), but the power range is 40–60, and ≥60 kW. Therefore, it can be concluded that Japanese tractors are represented for small-size agriculture, however, Russian and CIS countries tractors are represented for large-size agriculture. The number of

Japanese, Russian and CIS tractors available in each power range are shown graphically in figure 8.

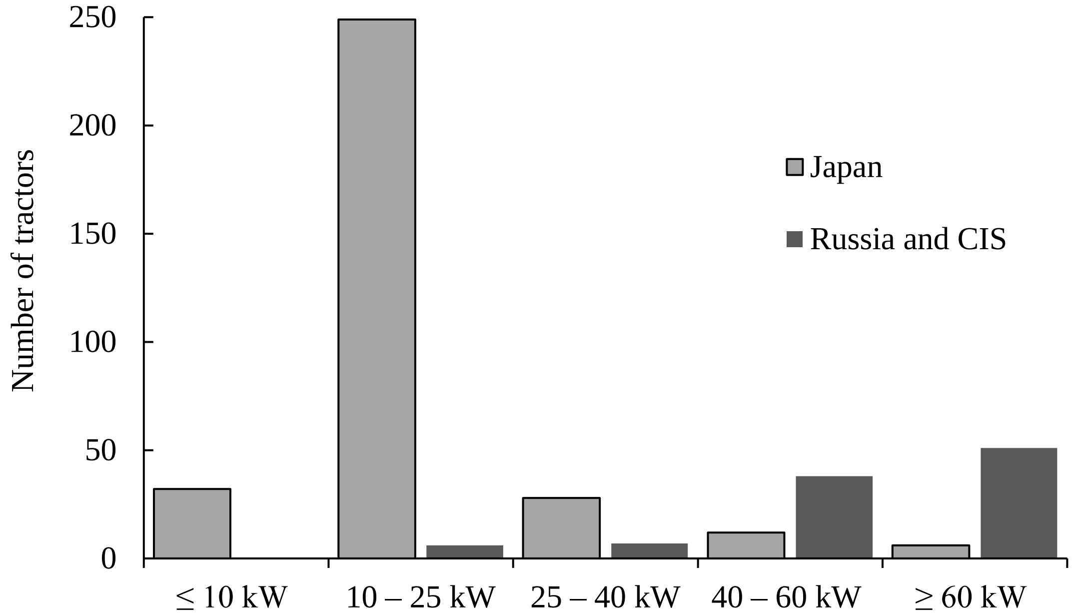


Figure 8. Number of Japanese, Russian, and CIS tractors in private PK market, May 30, 2020
Source: Drom.ru, 2020

In addition, the abundance of Japanese tractors in PK can be interpreted as high in demand among small agricultural producers due to the high quality and reliability of Japanese equipment. Also, the demand is boosted by a supply of second-hand equipment exported from Japan to local people in PK. Moreover, almost all Japanese tractors are equipped with additional equipment for soil cultivation, such as rotary cultivators and plows.

Tractors provided by Russian and CIS manufacturers tend to be larger and more powerful, from 40 kW and more, because these tractors are favored by agricultural enterprises, rather than individual farmers and small enterprises.

2.4 Research and agricultural machinery development in PK

The purpose of this section is to explore future opportunities for international cooperation between institutions providing agricultural machinery in PK. For this purpose, agricultural institutions in PK were investigated to identify the primary institution in the field of agricultural machinery research, as well as its current areas of research and development.

Agricultural machinery institutions

The PK has several agricultural institutes, which prepare specialists for agriculture and are engaged in machinery development for agriculture mechanization. These are the Primorskaya State Academy of Agriculture, Ussuriysk Agro-Industrial College, Chernigov Agricultural College, and Chuguev College of Agriculture and Service.

The primary institute for agricultural machinery, which deals with difficult issues of machinery development in agriculture and continuously contributes to the development of agricultural mechanization, is the Engineering and Technology Institute (ETI) of the Primorskaya State Academy of Agriculture (PSAA).

The fundamental efforts of scientists at the Engineering and Technology Institute are aimed at the development and improvement of agricultural machinery. Over the last five years, development has been aimed at improving and creating new agricultural machinery for soybean production, because soybeans are the leading agricultural crop in PK. The main areas of research that engage the institutes' students and scientists are agricultural machinery, materials science and technology for metal processing, mechanical engineering and repair, manufacturing automation and creation of automatic systems for animal husbandry, livestock production, and crop production.

Agricultural machinery research of ETI covers the study of all research efforts, such as the development of precise grain seeders, contribute to the exchange of experience and development among machine-plant enterprises in Russia and contribute to the development of agricultural mechanization of the AIC in PK. This provides an opportunity for a cooperation between the ETI and local PK agricultural enterprises in the field of agricultural mechanization, as well as cooperation with international institutions.

2.5 Conclusions

The findings of this chapter show that agricultural mechanization in PK has yet to be developed to its full potential. The current situation of agricultural mechanization in PK was briefly described based on the information gathered from the Statistics Office of the Russian Federation, scientific articles published in Russia, and own observations. However, the perspectives of agricultural mechanization that were obtained showed various directions for improving agricultural mechanization and productivity, especially specific data on machinery. The material and technical basis of production is the most important, and provides multiple avenues for improving agricultural production. In particular, modern agriculture requires the acquisition and adaptation of advanced technologies and machinery.

The overall PK status of the agricultural machinery market was analyzed to classify it and identify opportunities for expansion. It was found that there is a developed machinery market with all warranty and post-warranty supports, however, this machinery market mostly cooperates and appropriates with large scale agriculture. Besides, the private market, as well, has a significant role in small or private agricultural producers, that is why it will be always in good demand.

The analysis of research and agricultural machinery development in PK shows that among the agricultural institutions there are institutions with strong research activities in the field of agricultural machinery research and development. Thus, it might be a good opportunity for future international cooperations to take place with these institutions that develop agricultural machinery in PK.

These overall results can be evaluated as accurate indicators for managing agricultural mechanization and its development; however, it would benefit from controls for producing more reliable statistics. In particular, it is important to determine whether the agricultural mechanization level is in accord with the average field area and equipment size.

CHAPTER 3

RESEARCH SETTING APPROACH AND METHODOLOGY

3.1 Major issues and background

At present, the agricultural sector has become flexible and changeable to supply sufficient food for the world's population. In this challenge, farmers in several developing countries are looking for a new technology to increase crop yields and incomes, reduce the amount of fertilizer used, and decrease environmental damage to the atmosphere and water. These issues play a crucial role in the sustainable development of agriculture.

Meanwhile, literature review and personal experience revealed that agricultural producers in developing and developed countries mainly do not use all potential technological resources; they often make inefficient decisions in their agricultural production. There are usually two main reasons: business and lack of knowledge. The business definition can be described as an issue where agricultural producers do not want to invest much for a high cost of agricultural equipment and supplementary raw materials, as well as they are not concerned about prospects since the main goal is profit (invest less but get more). With the lack of knowledge or limitation of information sources, agricultural producers do not opt for new technologies, equipment, research achievements, and so on. Rather, they continue to utilize old technologies and principal agricultural techniques in order to survive the overall production needs. Moreover, it often combines both of the issues by one agricultural producer. Therefore, policy makers with scientists should identify the main important factors, which positively affect the level of productive efficiency in agriculture, then find suitable applied methods to recommend agricultural producers to grow their crops more efficiently through higher technological and economic efficiency (Patuk et al., 2018).

In terms of technological and economic efficiency in agriculture, the highest priority is to obtain the maximum yield increase and better crop quality with low-cost labor power requirements, as well as the technological aspects, such as the cost of agricultural machinery and equipment. Moreover, agricultural yield and quality generally depends on crop farming technology, soil cultivation performance (mechanization) and efficiency of the production as well as the environmental conditions. Therefore, the use of fertilizer application, and developing new fertilizer utilization technologies, as well as new cost-effective agricultural machinery, tools, and equipment for any scale of agriculture will always be a key point in sustainable agricultural development and productivity. However, for effective fertilizer application, it is always necessary to manage and consider factors that have an influence on this result.

Consequently, fertilizer application management should consider an optimum ratio of fertilizer times and rates, as well as reviewing equipment and the methods of application to increase efficiency of use (precision methods), crop yield, soil health to mitigate negative environmental effects, and farm profits. Therefore, one of the best currently applicable management fertilizer technologies that achieves these multiple benefits is a deep placement fertilizer technology (DPFT) (Takahashi et al., 1991; Tewari et al., 2005; Gaihre et al., 2016).

The advantages of DPFT have been proven by experts in several developing and developed countries. In Japan, by a scientific team from the Faculty of Agriculture of Niigata University, the DPFT has been proven as one of the best applicable technologies of fertilizer management toward yield increase and crop quality. It has been found that the deep controlled-release (slow-release) fertilizer (coated urea, lime nitrogen, phosphorus, and potassium) application at depths of 20 cm has a positive impact on plant growth, seed quality and yield of soybean plants (*Glycine max (L.)* Merr.). These positive effects were reached by the promotion of precision fertilizer fixation during all plant development stages, particularly over the reproductive stages (R1 – R6) (Takahashi et al., 1991; Tewari et al., 2005; Kaushal et al., 2006; Ohyama et al., 2010). In Bangladesh and China, some research has been carried out on fertilizer efficiency, environmental impacts of the fertilizer used, and crop productivity of deep placement fertilizer application in paddy fields. The results showed that the deep fertilizer placement from 5 to 20 cm, has significantly improved the overall nitrogen utilization efficiency by 20 – 50%, and crop yields by 5 – 25% on average compared to broadcast fertilizer application (soil surface application). Furthermore, it was found that a general decrease of mean nitrogen concentration by 60%, and pH by 3% in floodwater (Liu et al., 2015; Gaihre et al., 2016; Mazid et al., 2016). The main principle and advantages of the DPFT can be summarized as follows in figure 1.

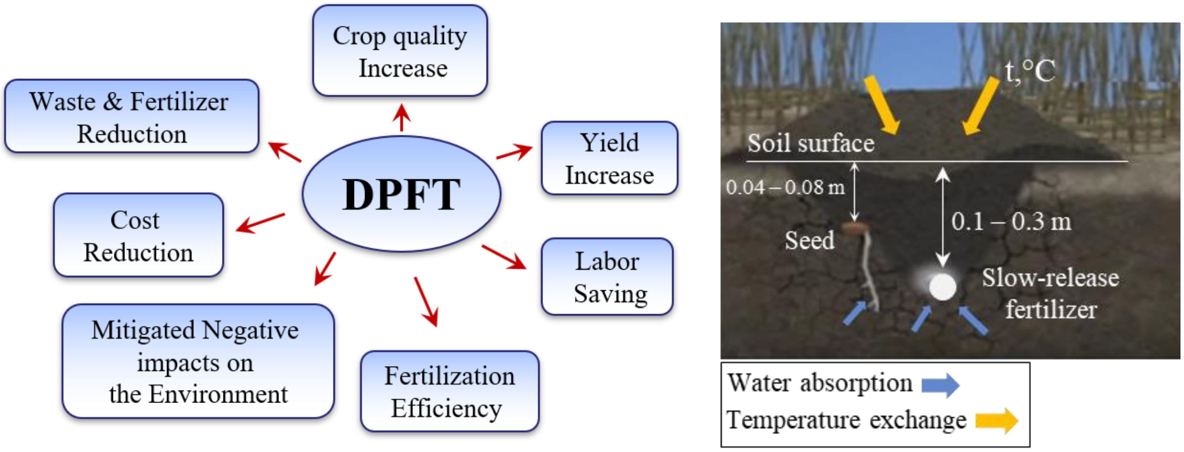


Figure 1. DPFT principle and advantages

Besides the benefits of DPFT, labor-intensive work is still required for deep fertilizer placement in some cases, whether it be for small or large scale agricultural practices. Therefore, to implement DPFT during the sowing of crops in different scales of agriculture, the development of mechanized deep fertilizer technologies, and new optimized deep placement fertilizer applicators (DPFA), and combined seeders, are necessary to be developed for subsoiling fertilizer, and tillage purposes (Liu et al., 2015).

3.2 Hypotheses

The primary disadvantage of DPFT in modern agriculture is the need for specialized sowing equipment (DPFT Seeders) to plant seeds with simultaneous application of slow-release fertilizers to receive all advantages from this technology. As DPFT is a relatively new technique, a new and different pieces of equipment has to be purchased or developed. Moreover, nowadays, on the global machinery market there are DPFT seeders with simultaneous fertilizer application, however, the cost of those seeders is high, compared to seeders without DPFT. In addition, there have been machinery and DPFT already developed for agricultural needs, especially in Japan, but, the small size of those machines is not suitable for large scale agricultural activities (Ohyama et al., 2017). For example, in Japan, the rotary tillage is used. It combines the seeder with a DPFT for soybean planting. This rotary tillage is essentially needed due to specific Japanese agricultural needs; however, it leads to a limited size and operating speed, which is one of the most important aspects for successful farming in Russia.

Therefore, in some cases, the seeders with DPFT which are available on the machinery market, are not suitable for large scale areas of Russian lands. Moreover, the high cost of the seeders with simultaneous application of deep fertilizers is the main limitation to the deep fertilizer application in Russia. Thus, the development (or modification) of conventional seeders commonly used in Russian agriculture may be a key factor in the shift to sowing with DPFT to increase land productivity. Besides, new optimized DPFAs need to be developed for subsoiling fertilizer application and tillage purposes. Figure 2 illustrates the main issues and solutions toward DPFT in Russia

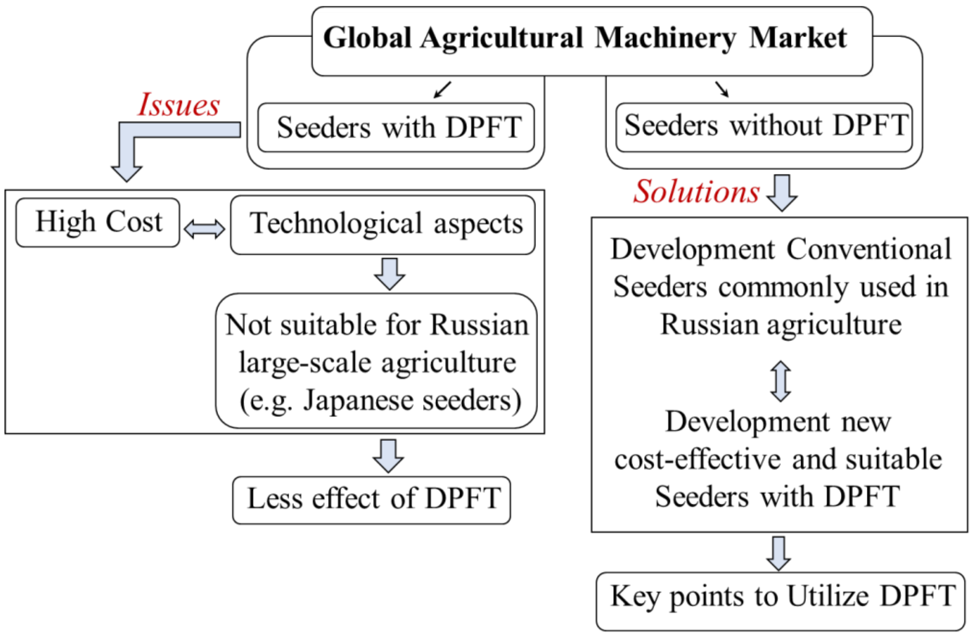


Figure 2. DPFT issues and solutions in Russian agriculture

In fact, fertilizer application should consider optimum time, rates, source, correct ratios and methods of application to increase efficient use, crop yield, soil health and farm profits, and to mitigate negative environmental impacts. Therefore, due to the limited knowledge of the DPFT, especially used in Russia, and the limited knowledge in design optimization of the DPFAs for production, brings to light that there is a necessity for fundamentals in practical research toward the implementation of DPFT in Russian agriculture with different technological aspects.

The primary study hypotheses can be summarized in following aspects based on the case of Russian agriculture:

1) Farmers (Agricultural producers) would undertake the DPFT for good aims in agriculture in terms of crop production increase if: DPFT and deep soil tillage

would show better quality and yields and increase by the reduction of fertilizer usages, labor-saving time, overall production cost, and mitigating negative impacts on the environment, based on their resource availability.

2) The improved (adopted) conventional agricultural machinery by DPFT, and subsoiling cultivation tools would be cost-effective and have high-performance characteristics to perform required tasks.
3) Soil productivity could be improved and the DPFT could be used for various types of crops.
4) The practical use of DPFT would be applicable for any scale of agriculture.

Hence, the key objective is to evaluate the practicability of using a conventional seeder of a Russian manufacturer, equipped with DPFT.

3.3 Research purposes

Based on the data and information of chapter 2, and based on the listed above issues and study hypotheses, the Ph.D. research purposes were determined to increase the state of existing knowledge of the DPFT, and generate new knowledge and solutions in the application of research on the DFPT in Russian agriculture.

The purpose of the Ph.D. research is to investigate a development of a Russian manufactured seeder by using the Deep Placement Fertilizer Technology, toward enhancing potential crop production with a primary focus on Soybean production (*Glycine max (L.)* Merr.) in Primorsky Krai, Russia. The main purpose of the development of a Russian seeder is to achieve a cost-effective model on the country's market with high-performance characteristics, which further could be equivalent to more expensive competitors on the global machinery market.

Furthermore, a Deep Placement Fertilizer Applicator will be designed and improved in order to have cost-effective and high-performance subsoiling tools, which could be utilized for crops cultivation purposes. Deep Fertilizer Applicators are still one of the most critical issues in developing agricultural tools in new agricultural machinery and Agro-technology.

The plan of the research can be briefly summarized as follows:

1) Design development of a deep fertilizer applicator and its fabrication.

2) Seeder prototype and technology development based on a conventional seeder of Russian manufacturing.
3) Practical laboratory and field experiments.

3.4 Materials and Methodology

3.4.1 Technology development

The technological idea of a new prototype seeder is to perform a deep application of controlled-release fertilizers with simultaneous soybean sowing for large scale agriculture. According to previous research, the average fertilizer application depth to achieve better crop yield and quality, as well as environment protection varies from 10 to 20 cm depths (Takahashi et al., 1991; Tewari et al., 2005; Kaushal et al., 2006; Ohyama et al., 2010; Liu et al., 2015; Gaihre et al., 2016; Mazid et al., 2016). Therefore, three main fertilizer application depths of 0.15, 0.20, and 0.25 m have been considered as the main technological aspects for the prototype and DPFA design. Figure 3 shows the main technological principal of the prototype.

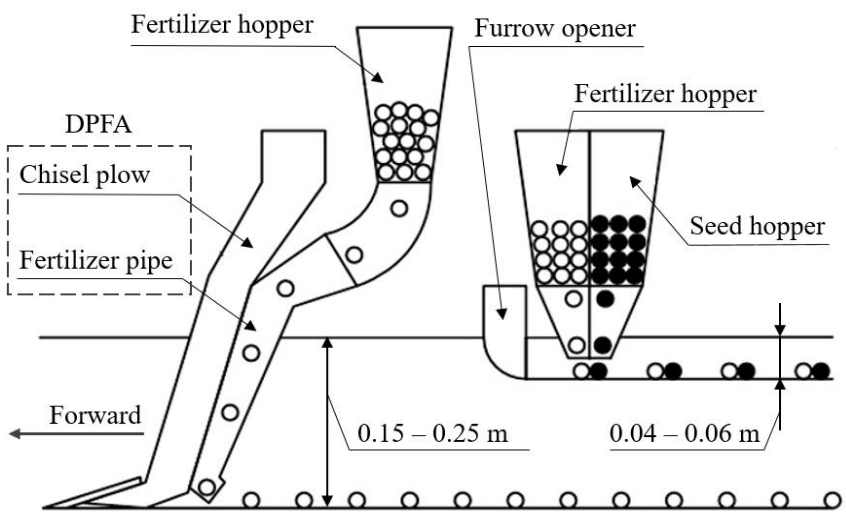


Figure 3. Method of DPFT with simultaneous soybean sowing

The proposed seeder prototype will be equipped with the DPFA which provides subsoil tillage and deep application of slow-release fertilizers at depths of 0.15 – 0.25 m., with simultaneous wide-row sowing of soybeans and application of fertilizers (base fertilizer) at the same time soybean sowing depth (0.04 – 0.06 m). Thus, this method of fertilizer application will allow plants to grow throughout the entire growing season by providing all-time essential nutrients.

Furthermore, this seeder prototype will be potentially used for other crops, for example, Maize (*Zea mays* L.). In addition, the prototype without seed-feeding mechanisms can be used for deep subsoil cultivation with fertilizer application before sowing crops by other agricultural types of machinery. Moreover, the model of developed DPFA itself could be adopted for any agricultural machinery.

3.4.2 Seeder prototype development

Deep placement fertilizer machinery and subsoilers have been successfully developed and improved recently. For example, in the research of Fujii et al. (2015) was the evaluation of tillage efficiency and power requirements of a rotary tillage implement combined with a deep placement fertilizer applicator. Zeng et al. (2017) discussed the method of modeling a deep tillage tool with heterogeneous soil by a discrete element model (DEM). It was found that better performance of the deep tillage tool was achieved at 5 – 20 mm deeper than the hardpan layer, where it has a greater bulk density than the topsoil layer. Hang et al. (2018) developed a subsoiling model by DEM for soil disturbance in different tine spacing of the subsoiler. It was later verified in a discrete element simulation, as well as in a field test with loamy clay soil. Topakci et al. (2010) and Ebrahimi et al. (2018) conducted practical research on life estimation and optimization of a deep tillage tool by the Finite Element Method (FEM) and through the performance of field experiments. Sandakov et al. (2019) optimized a chisel plow model by decreasing the mass and increasing its service life in a FEM (simulation software). Moreover, recently, Wang et al. (2020) conducted field experiments on the evaluation of a biomimetic shark-inspired subsoiler for the reduction of tillage resistance to optimize the subsoiler parameters, as well as to improve the soil productivity.

Certainly, all listed studies above have a significant value in agricultural machinery and subsoilers' development. However, these studies still have limited applied knowledge regarding the utilization of DPFTs and the optimization of DPFAs. Therefore, new study results and research based on new seeder prototype development will have a significant value for machinery development, particularly in Russian agriculture and mechanization.

This Ph.D. research is based on a modification from a Seeder for a Sugar-beet Tractor (SST) (also named as model number 8 (A) and 12 (B)) made by a Russian manufacturer and equipped with DPFT. This seeder is commonly used in Russia, due to its simplified design and its availability on the market. Also, it does not require a high-power consumption, and it has a practical possibility to extend work width by a section adjustment. In addition, the seeders' availability and technical principles analysis were made to consider the best option for a new seeder prototype (Patuk et al., 2018).

The seeder SST is a precision seeder designed by a Russian manufacturer for sowing calibrated seeds of sugar-beet, as well as for legume crops (soy, beans, buckwheat, and millet) with simultaneous application of granulated mineral fertilizers. Figure 4 shows a schematic of the seeder.

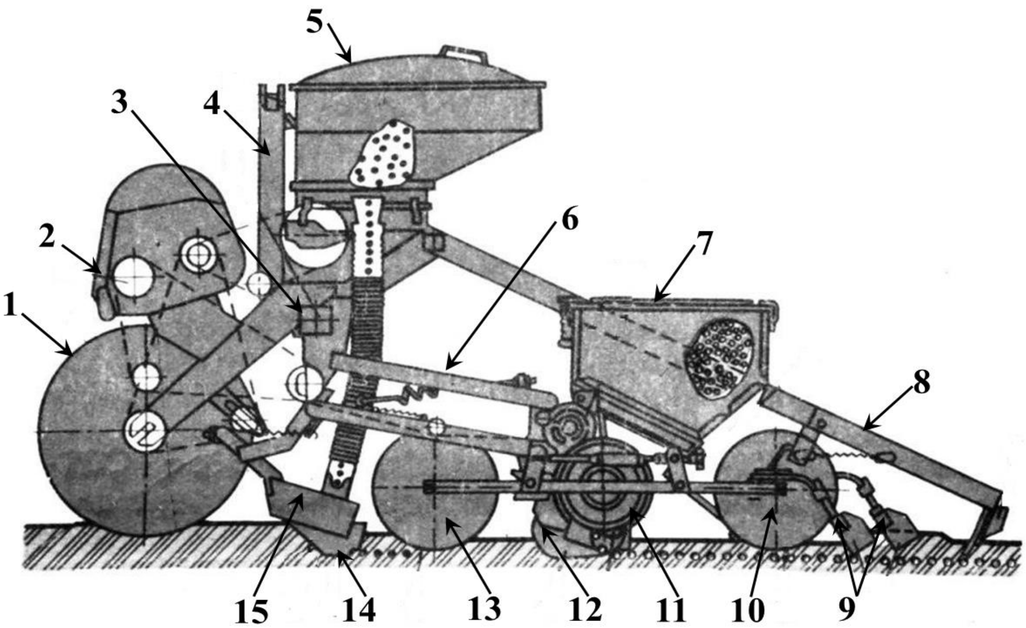


Figure 4. Schematic diagram of seeder SST (Side view)

1 – Driving-support wheel; 2 – Reduction gear; 3 – Frame assembly; 4 – Hitch linkage; 5 – Fertilizer hopper; 6 – Suspension of seed-feeding mechanism; 7 – Seed hopper; 8 – Following marker; 9 – Seed coverers; 10, 13 – Press (Suppression) wheels; 11 – Seed-feeding mechanism; 12 – Seed furrow-opener, 14 – Fertilizer (applicator) furrow-opener; 15 – Clods protection.

However, the basic version of the seeder applies base fertilizer at depths of 0.02 – 0.06 mm as the same crop sowing depth. Therefore, the modification will allow us to use deep fertilizer application by removing parts 14 and 15 (Fig. 4). Through the implementation of a newly designed DPFA, the placement depth of fertilizers will be extended to 0.15 – 0.25 m. Moreover, the operating performance characteristics with the simplified design of the seeder required minimal changes to modify the proposed technology. Therefore, for research purposes, it was advantageous to approach this. Table 1 presents specifications of the seeder SST based on two models' range.

Table 1. Specifications of SST (8 – 12)

Category, Unit	Range value
Operating speed, km/h	3.6 – 7.2
Working width, m	4.8 – 5.4
Row spacing, m	0.45 – 0.6
Seeding rate, pcs/m	8 – 35
Fertilizer rate, kg/ha*	30 – 150
Depth of seeds and fertilizers, m	0.02 – 0.06
Volume of seed hopper, dm^3	128 – 192
Volume of fertilizer hopper, dm^3	180 – 270
Required tractor power class, kN	1.4 – 2.0
Operating dimensions, mm and Mass, kg	
Width, mm	5,730
Length, mm	2,275
Height, mm	1,120
Mass	960 – 1,144

Note: * Fertilizer rate is given in average value

Source: Klenin and Egorov, 2005.

Seeders SST-8 and SST-12 are similar in design, the difference is only in the number and arrangement of sowing and fertilizer feeding mechanism sections. Therefore, in Tab.1, the specification is given for both models.

3.4.3 DPFA design development

The design of the DPFA was based on a chisel plow model by Sandakov et al. (2019), which was proposed for grain production in Russia. The model was designed and analyzed in a FEM simulation by static analysis with a total applied force of 5,000 N. The chisel plow model has an optimum shape with four holes within a shank for a frame attachment. The knife of the chisel plow has a fixation to the shank by two bolts connecting under a down part of the vertical plane of the chisel plow. However, it was targeted to design a new DPFA plow, which would not only be satisfactory with technical issues for soybean cultivation but meet the issues of conserving resources due to its streamline design. Figure 5 shows the overall view of the chisel plow. Moreover, the material properties of the chisel plow are specified in Tab. 1 in App. 2.

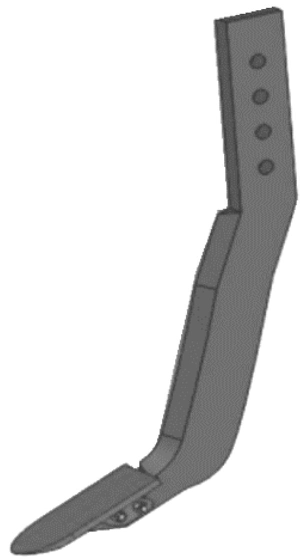


Figure 5. Chisel plow model

The main study tasks were to design a new DPFA by improving the shape of the chisel plow. From selecting optimum material properties for its further manufacture, and developing a fertilizer pipe, which will be attached to the plow, and simultaneously perform deep tillage and deep placement fertilizer application. Furthermore, since the maximum subsoiling operating depth is expected to be 0.25 m and the DPFA will be the first prototype model, it was targeted to have a minimum safety factor (SF) between 2 and 2.5 for its material property. This minimum SF will not allow the DPFA to bend or break due to unpredictable working conditions in the soil (e.g. mixed soil structure with different objects in the soil, a heavy soil property etc.). Moreover, this SF will promote an increasing effect to the DPFA's service life.

The FEM simulation software (AutoCAD Fusion 360, Autodesk, Inc.) was used as the main technique for the DPFA design and testing, which is commonly used to design and develop parts for machines and machine prototypes (Zienkiewicz et al., 2005; Topakci et al., 2010; Malón et al., 2015). The FEM simulation allowed the performance of a simulation on the DPFA to evaluate the mechanical behavior through stress and strain analysis of the static simulation. This simulation was needed to analyze the mechanical behavior of the DPFA and to select the optimum material properties, as well as to acquire the locations of stress concentrations on the DPFA where strain gages can be attached for practical experiments.

The DPFA includes a design of a 3D model with the needed overall dimensions and generated mesh completed in the 3D simulation program. A further step is a selection of material properties in the 3D simulation program with optimum yield and ultimate strength to control the optimum SF. For ductile materials, the SF is expected to be checked for both yield and ultimate strengths. Since the yield strength calculations will define the SF until the part starts to deform plasticity, however, the ultimate strengths result will define the SF until it reaches part failure. This mechanical method is used in the mechanical engineering industry to determine the elastic deflection for ductile materials (Radovic et al., 2004; Miljojković et al., 2017). Thus, the SF will be assumed and calculated automatically in the 3D simulation program.

The final steps are the use of static analysis by exploiting a range of loads with different constraints (boundary conditions) to the selected geometry, and the analysis of the results from the simulation so as to define material properties with an optimum SF for further manufacture. According to the study by Topakci et al. (2010), the maximum draft force of each subsoil tine had 12.773 kN at the working depth of 0.45 – 0.75 m. In the study by Sandakov et al. (2019), in the static analysis, the total applied force of 5,000 N was simulated on the chisel plow. In addition, the soil moisture content and soil compactness were important to consider since it will have a significant effect on resistance forces in field experiments (Lisowski et al., 2016) Unfortunately, there were no existing studies on draft force and soil resistance properties such as soil compactness and assumptions related to soil moisture in PK, Russia. Therefore, for the purposes of this study the static analysis of the DPFA was considered. A maximum force of 6,000 N was applied for the depth of 0.25 m based on the result of Topakci et al. (2010) and Sandakov et al. (2019). Moreover, for the static simulation, the depths of 0.15 and 0.20 m were considered, and forces of 4,500 and 5,000 N were applied, respectively. Thus, based on the described methods, the optimization algorithm of the DPFA design was developed and given in figure 6.

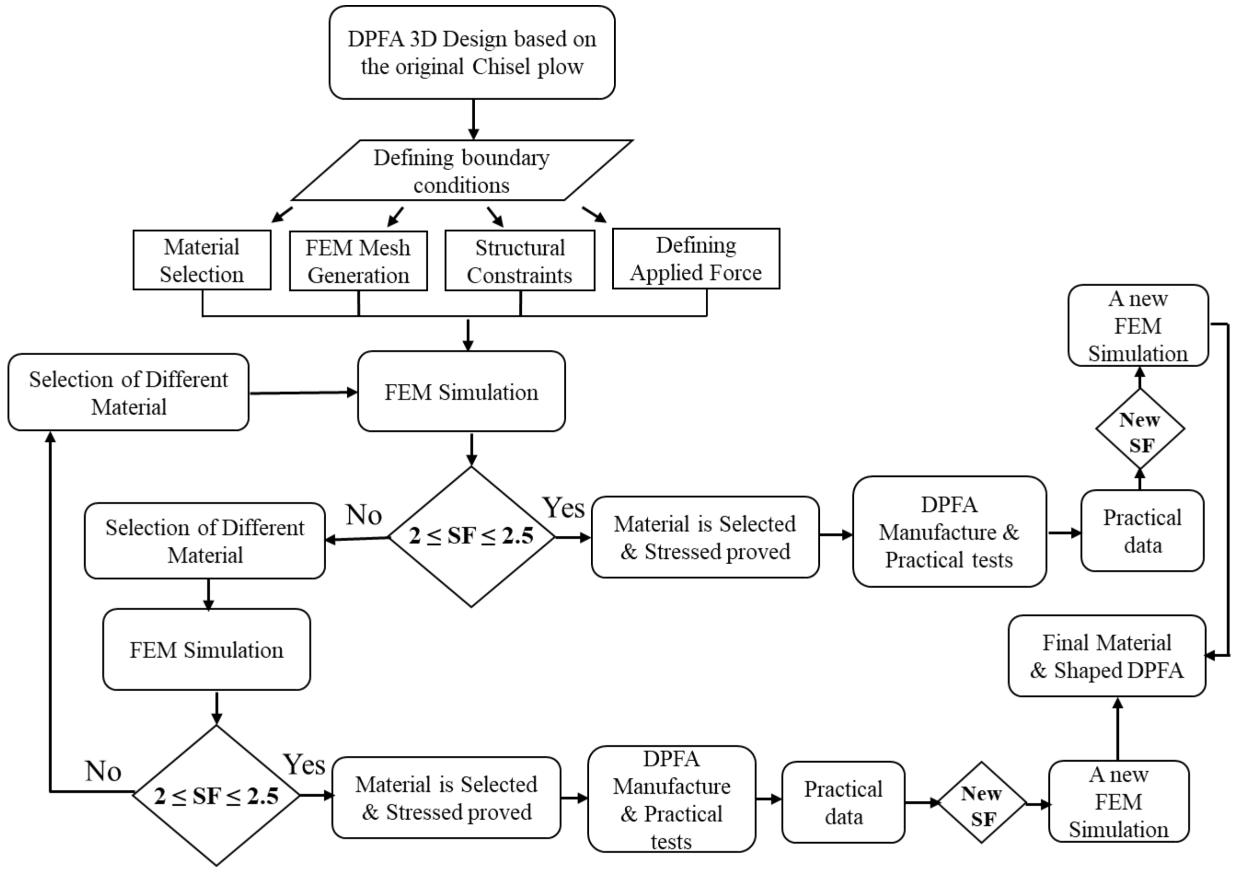


Figure 6. Flow chart of the DPFA design algorithm

This algorithm summarizes the information introduced above in the section of DPFA design development as a block diagram, which is used as one of the technical methods to optimize the DPFA and the seeder prototype in this study. In addition, in order to create the final DPFA model, as well as practical data on the seeder prototype, this algorithm is needed to obtain and combine practical data with simulation data to achieve accurate results for further improvements.

3.4.4 Laboratory and field experiments

Laboratory setup and strain gage equipment

In order to simulate and apply the static load (force) to the DPFA in laboratory conditions, a laboratory setup is developed. The main purpose of a laboratory simulation experiment is to measure strain resistances by applying a static load on a DPFA with attached strain gages in laboratory conditions. These measurements are needed to obtain data on strain gage resistance and calibrate strain gauge equipment before field experiments to calculate traction resistance and soil resistance (compactness). Figure 7 shows the main features of the laboratory setup.

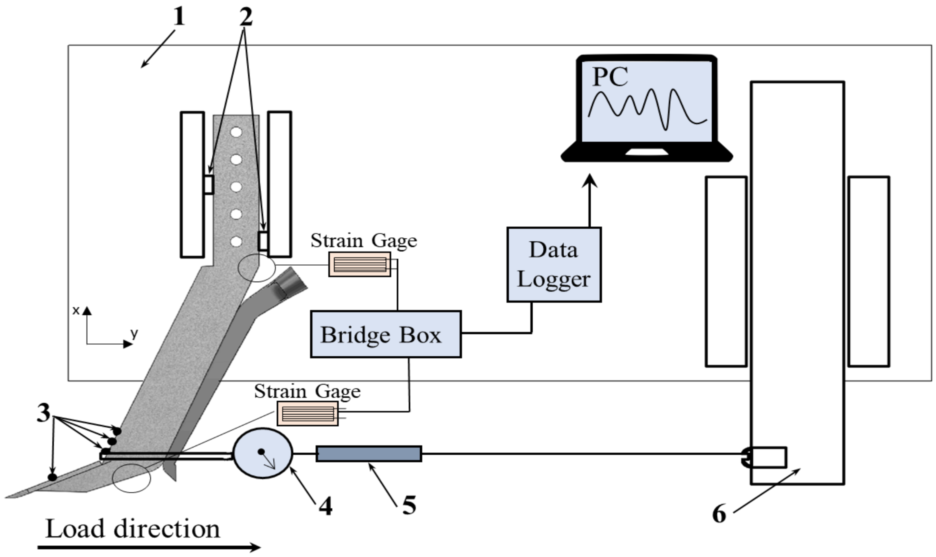


Figure 7. Laboratory setup

1 – Metal worktop; 2 – Adjustable boundary conditions of bolt connectors; 3 – Applied force centers; 4 – Dynamometer (Max. 5,000 N); 5 – Adjustable load turnbuckle; 6 – Adjustable bracket depth.

The main idea of the laboratory arrangement was to fix the DPFA on a worktop and apply an interval static load. This configuration was made on a metal worktop, and all parts were fixed by an arc welding. In order to simulate the different frame fixations of the DPFA, it used two adjustable cylinders (Fig. 7 (2)) with a diameter of 19mm. Furthermore, to simulate different soil depths (0.15, 0.20 and 0.25 m), its determined force (loads) centers (Fig. 7 (3)). In addition, in figure 7 are shown expected attachments (stress concentrations) of the strain gages.

To perform a laboratory simulation and field experiments, the strain gages, data logger amplifier with data acquisition software and the bridge box were manufactured by Kyowa Electronic Instruments Co., Ltd. Japan. Two types of foil strain gages (KFGS-30-120-C1-11 L5M2R and KFGS-20-120-C1-11 L5M3R) were used with the 2 and 3-wire systems, as well as different gage widths and lengths in order to capture and identify different strain resistances. The EDX-100A-4 data logger amplifier with the DCS-100A data acquisition software was used to record data manually and periodically with different time intervals. The one-touch type bridge box (DBV-350A-8) was used to connect the strain gages with the data logger amplifier. Figure 8 shows the pictures of the main equipment.

a) b)

Figure 8. The used data recorder equipment

a) – Data logger amplifier (EDX-100A-4); b) – Bridge box (DBV-350A-8)

All the equipment and technical support were provided by the Laboratory for Bioproduction and Machinery of the Faculty of Agriculture, Niigata University.

Field experiments

The field experiments are performed in order to test practically the developed seeder prototype and technology with different methods of soybean sowing. Since it was necessary to prove the developed DPFT by soybean sowing with different fertilizer depths, as well as a phenological observation on soybean development. The field experiments are conducted on the side of PK, Russia. Figures 9 and 10 show the field location on the side of PK, and the scheme of the field experiments.

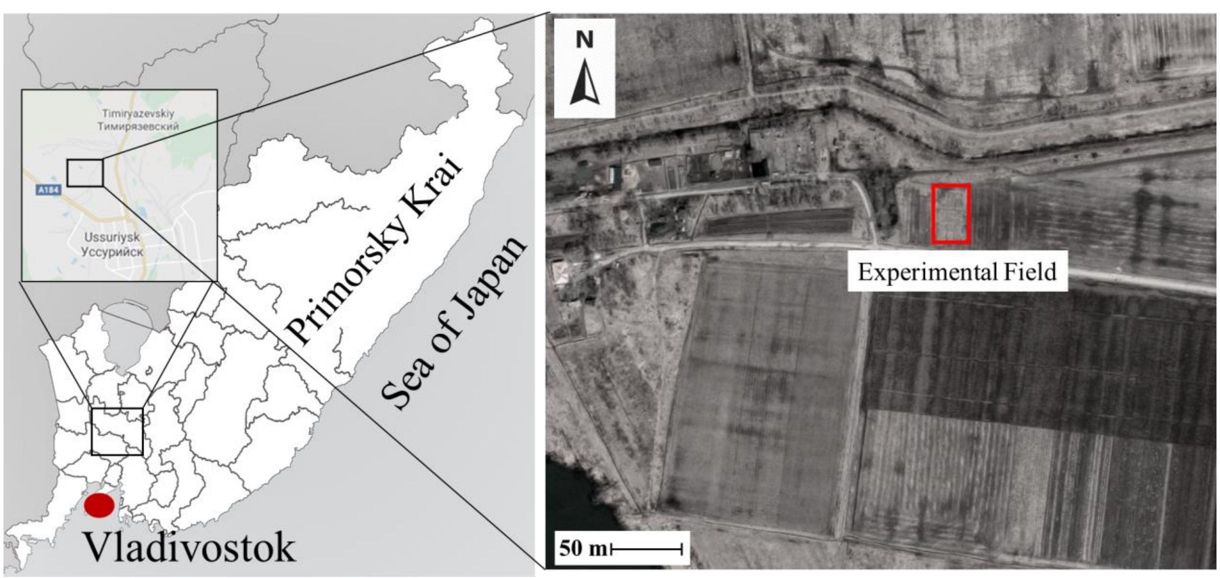


Figure 9. Experimental field location, Ussuriisk, PK, Russia (43°52'11.1"N 131°56'04.9"E)

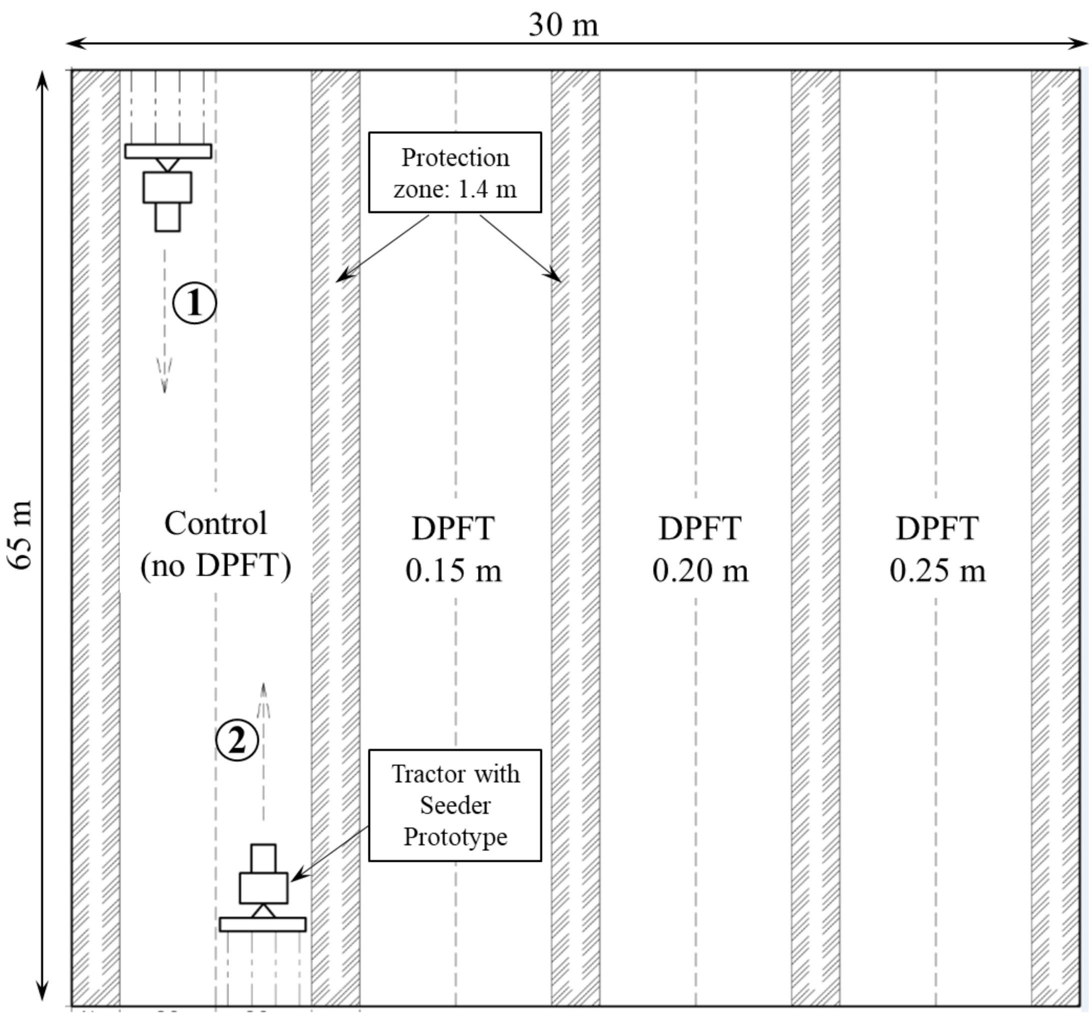


Figure 10. The field experiments scheme

The control plot will be carried out by the prototype without DPFT application, in order to compare with the significance of DPFT usages depending on different fertilizer application depths. Moreover, different seed spacing will be considered on each plot. For instance, numbers of 1 and 2 (Fig. 10) show the direction of sowing, as well as different seed spacing of 0.05 and 0.10 m, respectively. The different spacing of 0.05 and 0.1 m were considered as one of the commonly used seeds spacing and a seeding rates of soybean sowing in precision agriculture in PK, however, the row spacing is expected to have 0.7 m between rows. This ‘wide-row’ spacing of 0.07 m was considered as one of the main technological aspects of the developed seeder prototype to provide maximum sunlight and air exchange, as well as soil cultivation practices.

3.5 Conclusions

In this chapter, information on the main issues, study background, an assumed hypothesis is explained and given upon the primary study purposes, as well as the study materials and methodology, which are described. Hence, the proposed technology and seeder prototype development are focused on a seeder, manufactured in Russia and currently commonly used. Consequently, the main purpose is to achieve a new seeder model with DPFT for Russian agriculture. The study methods were a combination of designed theoretical methods (computer simulation methods (CAD)), as well as practical methods. For example, laboratory and field experiments on seeder prototype and soybean plant development. Therefore, it is always necessary to verify theoretical results with practical results, including further adjustments to obtain accurate results.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Design of DPFA

All subsoiler tools have an essential purpose in principal-tillage of soil cultivation and overall mechanization, and play a specific role in labor-saving work. These tools are mostly applied to break through compacted or impervious soil layers to improve air and water exchange, and the main shape is mostly based on a chisel-type implement tool (Bainer et al., 1956; Kepner et al., 1978). However, DPFA design has more specific features since it combines subsoil tillage with simultaneous deep fertilizer application; therefore, these specific features have to be considered in its development. Moreover, agricultural machinery manufacturers produce machinery and tools such as conventional plows, harrows, chisel plows, and other implements with significant quantity and excessive design, which reflects by over mass and size with safety factors. Therefore, improvement by way of streamline design would significantly reduce the amount of used material and the final cost of agricultural machinery (Yurdem et al., 2019).

As it was explained in Chapter 3 (subchapter 3.4.3), the DPFA design was based on a chisel plow model, which was made by *Sandakov et al.*, and proposed for grain production in Russia. Since it was the initial chisel plow, the model was excessively designed for subsoil cultivation, and general conditions conducted through the static analysis in FEM simulation for its model. Therefore, a new model of DPFA was designed and conducted a new FEM simulation analysis according to a new seeder prototype model and DPFT. In addition, the new DPFA model which was re-designed, is not only satisfactory with our technical issues for soybean cultivation but meets the issues of conserving resources due to its streamline design.

At the first step of the experiment, the DPFA was designed to satisfy the technical requirements of the deep fertilizer application. The main issue was to perform deep tillage and simultaneously apply fertilizers into the soil at a depth of 0.15, 0.20, and 0.25 m. Next, the developed fertilizer pipe of fertilizer transportation should not increase the tractive resistance (draft force) made by the chisel plow. Therefore, the total width of the fertilizer pipe was designed at 18 mm, which is less than the total thickness of the shank (24 mm). In addition to this, the fertilizer pipe has a round inlet and square outlet, and the pipe has a truncated shape reduced by 10 mm from the top to the bottom of the pipe. Figure 1 shows a schematic diagram of the designed DPFA with overall dimensions (mm). In addition, figure 2 illustrates a schematic of the designed fertilizer pipe showing a view of the different sections in order to reveal the inside shapes of the pipe.

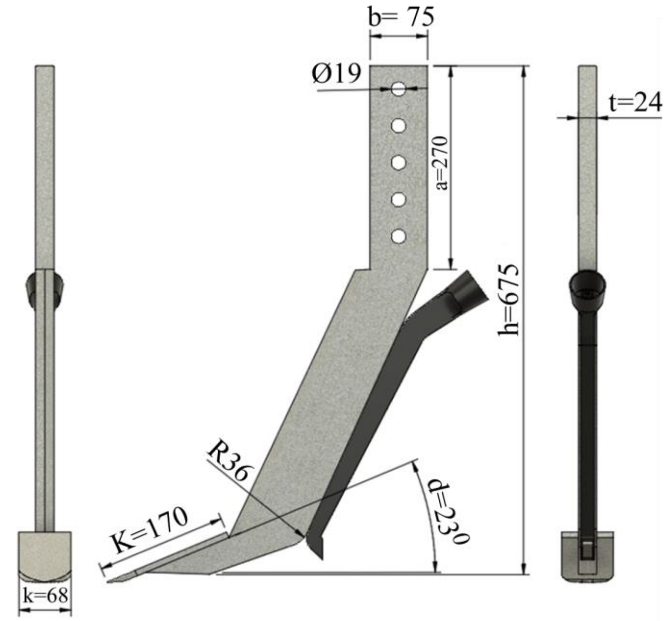


Figure 1. Schematic diagram of the DPFA

a – Height of the frame connector; b – Width of the shank; h – Height of the shank; K – Length of the knife; k – Width of the knife; R – Radius of curvature of the shank; d – Penetration angle; t – Thickness of the shank.

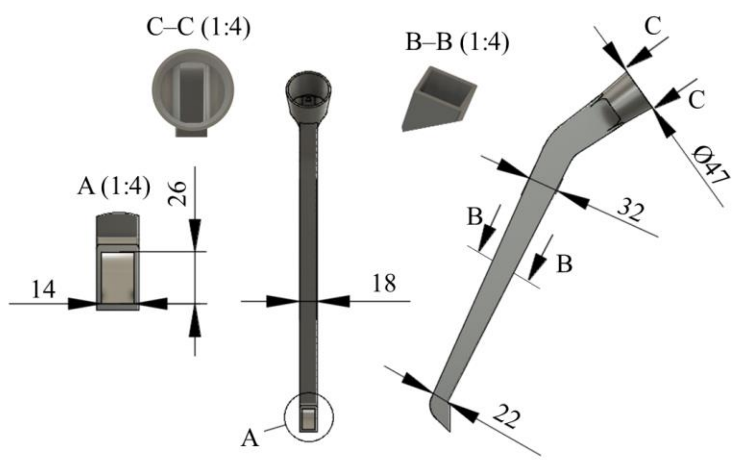


Figure 2. Schematic diagram of the fertilizer pipe

A – Zoomed view of the square outlet; B-B – Section view of the middle of the pipe; C-C – Section view of the inlet; Fertilizer pipe thickness – 2 mm.

Furthermore, the DPFA was designed with five fixation holes to adjust to the three depths for the seeder prototype. Therefore, it was convenient to simulate accurately the different applicable depths for different simulation conditions. Furthermore, the knife fixation to the shank and the fixation of the fertilizer pipe to the shank were not considered in this design since this is the first DPFA prototype. These fixations were simulated as if it fixed by an arc welding and had a full body connection. However, the different material properties of the knife, chisel shank, and fertilizer pipe were considered.

After a completed design, a finite element model of the DPFA was done. Moreover, to achieve the proper accuracy of computations with an optimum 3D model mesh size, therefore, the mesh sensitivity analysis was conducted. Additionally, in the study (Kamal et al., 2013), it was discussed that the stress values do not change by an appreciable amount by decreasing the mesh size. However, there was a significant increase in the nodes and elements number of a model. Therefore, it has resulted in a rise in the processing time and data storage requirements without much significance in the accuracy of the final stress results. Thus, the mesh of the DPFA model was meshed and calculated by the Fusion 360 software based on Model-Based Size (Average Element Size) of 1 – 10%. Also, all edges of the DPFA model were filleted (rounded) by the radius of 2 mm to reduce the stress concentrations. The numerical model is shown in figure 3, which consists of 116,134 nodes and 66,221 elements. Figure 4 shows in detail mesh size depending on different areas on the DPFA. The summarized result of the used mesh is given in Tab. 2, appendix 2.

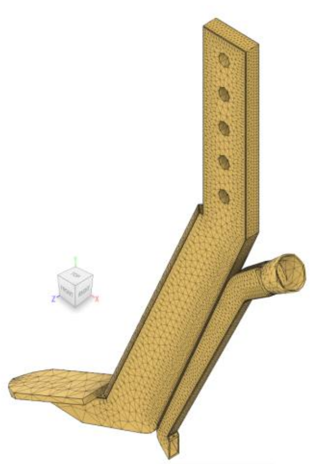


Figure 3. Overall DPFA finite element model and meshing structure

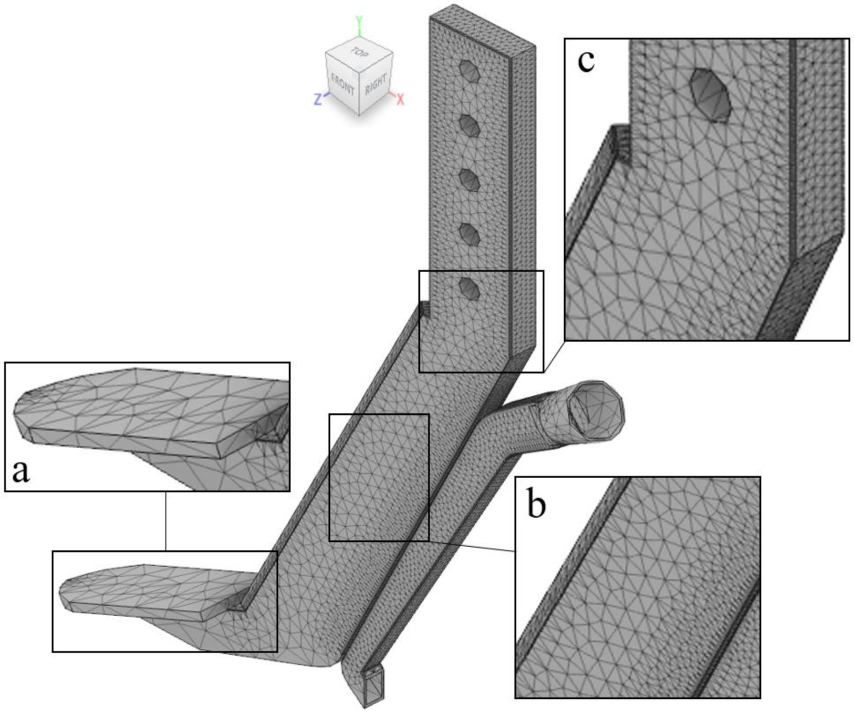
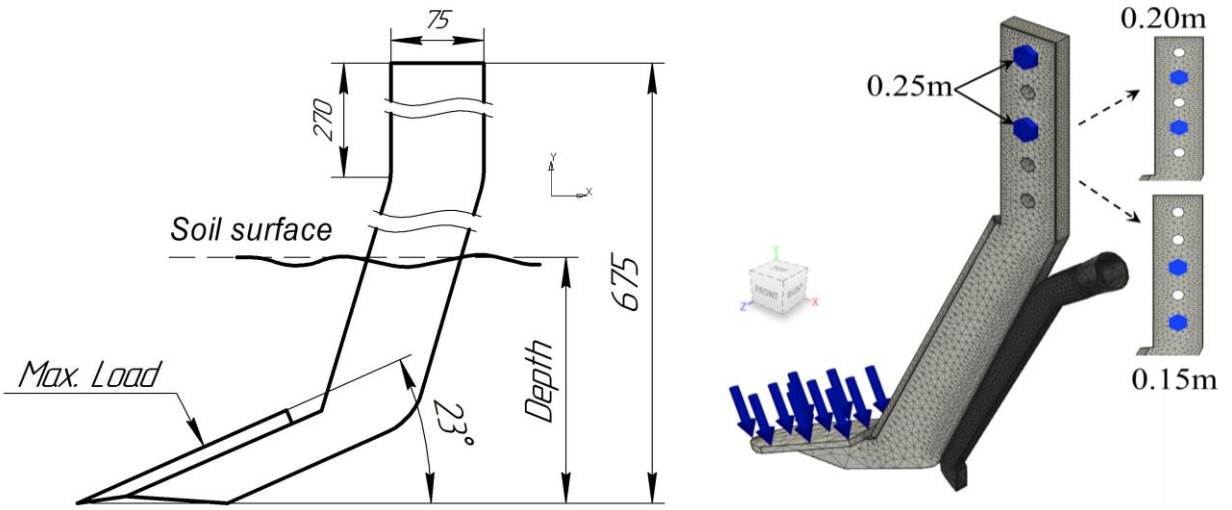


Figure 4. The detailed mesh structure of the DPFA

a) – Area of the knife (Max. mesh size); b) – Middle area of the shank (mesh changes over from middle-sized to small size); c) – A highly stressed area of the DPFA.

According to figure 4, the mesh size is distributed differently in all DPFA areas. This effect can be explained with the fact of the different stress distribution points inside the body; therefore, the mesh was calculated automatically depending on potential stress distribution, based on the model size with average element size (1 – 10%). For instance, the area of the knife (a, (Fig.4)) has the largest mesh size compared to the main body (b and c, (Fig. 4)). Consequently, this method has recognized areas with significant importance for the DPFA shape and SF improvement without additional simulation operations.

Furthermore, the maximum load will be evenly distributed throughout the subsoil area of the DPFA; therefore, in the simulation boundary conditions, the different static load was applied on the maximum subsoil area (surface of the knife) in the opposite to the forward direction of the DPFA. The base of the boundary condition and boundary conditions of the static simulation are given in figure 5.



a) b)

Figure 5. Boundary conditions

a) – *Max. Load* – Max. load at subsoil area; *Depth* – All subsoil area; b) – 0.15 m – load 4,500 N; 0.20 m – load 5,000 N; 0.25 m – load 6,000 N; bolts connector – 19 mm.

The next steps were based the selection of the material properties to achieve the defined SF through multiple experiments within the simulation in accordance with the DPFA design algorithm (Fig. 6, Ch. 3). Therefore, the results of the static analysis for the maximum subsoiling operating depth of 0.25 m with the applied force of 6,000 N (which requires the optimum safety factor of $2 \leq SF \leq 2.5$) is presented graphically in figure 6. Additionally, the static analysis result for the depth of 0.15 and 0.20 m with the results summary is presented in appendix 2 (Fig. 2 and 3).

Consequently, it was necessary to analyze and understand the material behavior of the DPFA under the most considerable applied force in order to predict stress areas and potential locations for strain gage attachments. Moreover, the initial simulation analysis has the most significant value in further shape optimizations.

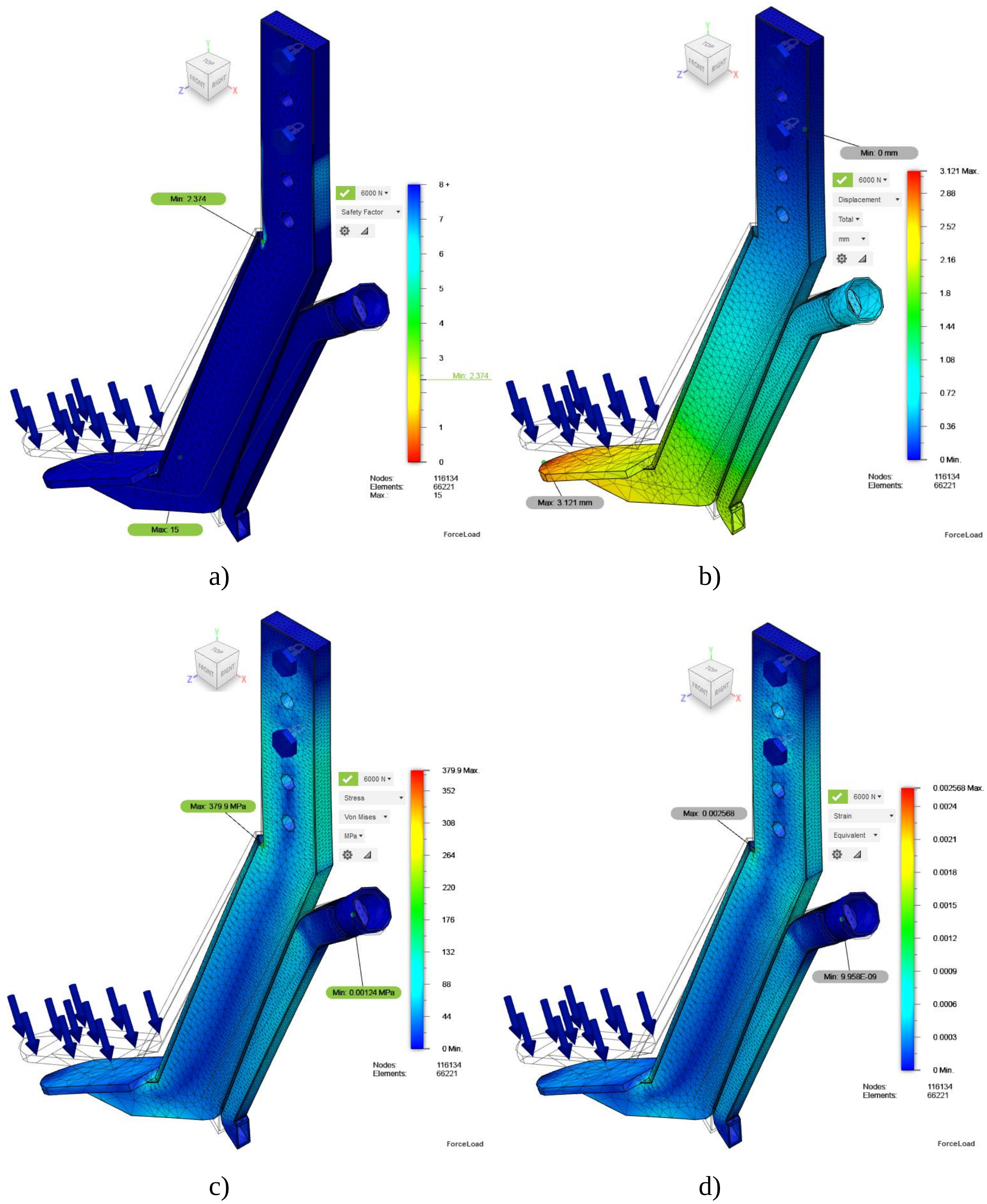


Figure 6. Results of the static analysis of the DPFA*

a) – Safety factor; b) – Displacement; c) – Stress; d) – Strain Equivalent

* Reaction force, Contact pressure, and Detailed 3rd strain principals are given in App. 2 (Fig. 1).

According to the static simulation results (Fig. 6, (a)), the minimum SF is 2.3 per body under loaded force of 6,000 N. The SF is a ratio of the maximum strength of the selected material to the stress calculated in the simulation. It was shown that the calculation result was based on the yield strength. Thus, this SF target meets the set optimum SF ($2 \leq SF \leq 2.5$), and the DPFA design is not expected to be bent or broke with the current force load and analysis criteria. Moreover, the simulation shows the minimum SF of 3.1 for the depth of 0.15 m and a force load of 4,500 N, as well as 2.8 for 0.20 m with 5,000 N, respectively. Table 1 summarizes the optimum material properties for the DPFA used in the static stimulation.

Table 1. Material properties used in the simulation

DPFA part	Shank	Fertilizer pipe
Properties, Unit	Steel AISI 4135 QT	Steel
Density (kg/m^3)	7,860	7,850
Young’s modulus (GPa)	207	205
Yield strength (MPa)	780	207
Ultimate Tensile Strength (MPa)	950	345
Modulus of Elasticity (GPa)	205	185
Bulk Modulus (GPa)	160	160
Shear Modulus (GPa)	80	75
Poisson's Ratio	0.33	0.29
Mass (kg)	11.2	0.58

According to table 1, one of the suitable materials for the chisel shank, as part of the main DPFA body to achieve the set SF, is the AISI 4135 QT steel. However, this is a comprehensive proposal based on the simulation conditions. Furthermore, the further selected material for the manufacture of the DPFA may not be appropriate to a particular industry or application due to specific working conditions or other factors relevant to cultural expectations by way of farming. Therefore, different types of material properties were used for the static stimulation where the yield strength was varied from 350 to 900 MPa, and the ultimate strength was varied from 420 to 1,000 MPa. Thus, it was found that for this shape of the DPFA to achieve the minimum SF from 2 to 2.5, the main material properties of carbon steel should possess high yield strength of 800 MPa and ultimate strength of not less than 900 MPa, using Young's Modulus of 207×10^{-3} MPa with Poisson's Ratio of 0.33. Additionally, it is constantly required to consider all physical and mechanical properties to control a wear-resistance property depending on working conditions (Sasaki et al., 1982; Tavio et al., 2018).

In conclusion, the static simulation result of the DPFA model with a 6,000 N[3] load can be summarized as follows:

- Minimum SF of 2.3 (for the main body) (Fig. 6, (a));
- Maximum displacement of 3.1 mm (Fig. 6, (b));
- Maximum stress of 379.9 MPa (Fig. 6, (c));
- Equivalent maximum strain of 25.6×10^{-4} mm/mm (Fig. 6, (d));
- Total reaction force of 5,642 N (Fig. 1, App. 2 (a));
- Total contact pressure of 207 MPa (Fig. 1, App. 2 (b));
- 3rd Strain principals: Max – 5.263E-06, Min – 0.002122 (Fig. 1, App. 2 (c, d)).

A brief result summary of the static stimulation for 4,500 and 5,000 N is specified in tables 3 and 4 (App. 2).

Moreover, referring to material properties of the original chisel plow (Tab. 1, App. 2) the yield strength and ultimate strength are much less than it was obtained in the simulation. This result occurred because it used a greater applied force than in the previous study. However, the total mass was reduced by 0.26 kg since the overall design of the original chisel plow was changed.

Besides, the stress and strain analysis of the static simulation showed the most stressed areas where there are stress concentrations on the DPFA and areas of expected breaks. These two criteria are essential to improve the future machinery design, parts and practical experiments (Celik, and Akinci, 2016; Celik et al., 2018). As an example, the stress analysis showed the areas where strain gages can be attached for practical experiments to obtain soil resistance force and strain-induced effects on the DPFA.

[3] The detailed results of the simulation of 0.25 m depth with 6,000 N loaded force are given in Tab. 5 (App. 2).

4.2 Laboratory experiments

The laboratory experiments, as well as DPFAs manufacture and seeder prototype development, were conducted at the ETI of PSAA (43°46'40.1"N 131°57'08.0"E), by the SICR in the field of agriculture under the auspices of MAFF, Japan. The main purpose of laboratory experiments was to measure strain resistances by applying a static load on the DPFA with attached strain gages to the stress concentration areas acquired by a FEM simulation. These measurements are needed to obtain data on strain gage resistance and calibrate strain gauge equipment.

Based on the results of the simulation and material properties, DPFA prototypes were manufactured, and strain gages were attached. Four DPFAs were manufactured manually from sheet metal by a metal cutter and arc welding. Figure 7 briefly illustrates the manufacturing process.

Figure 7. The manufacturing process of the DPFA

After the DPFAs manufacture was completed, the strain gages were attached to the DPFA, and the DPFA was fixed to the laboratory setup. Consequently, figure 8 shows the stressed areas obtained by the simulation, where the strain gages were attached. Figure 9 illustrates the fixed DPFA to the laboratory setup.

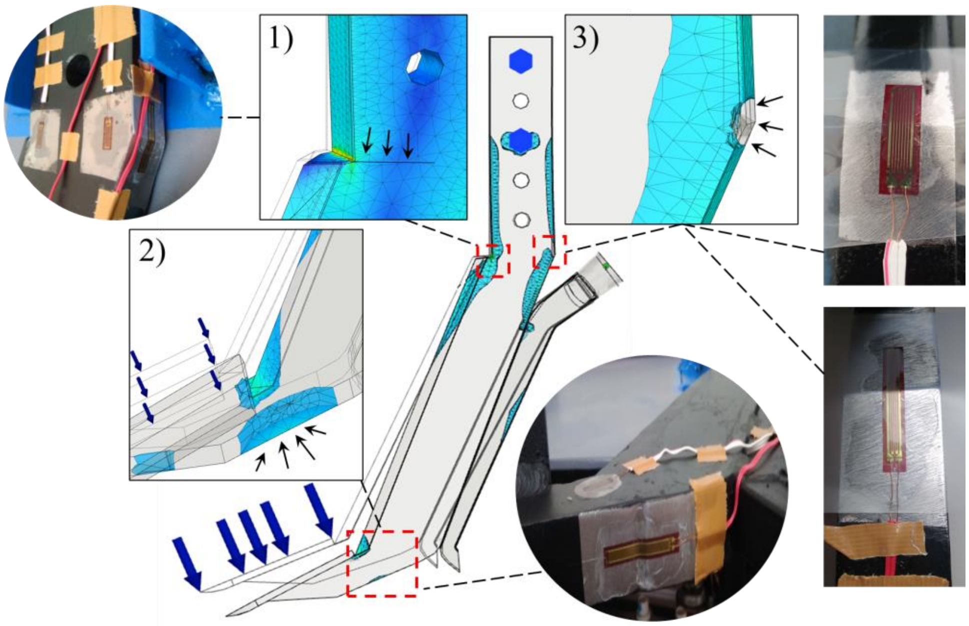


Figure 8. Stressed areas with attached strain gages

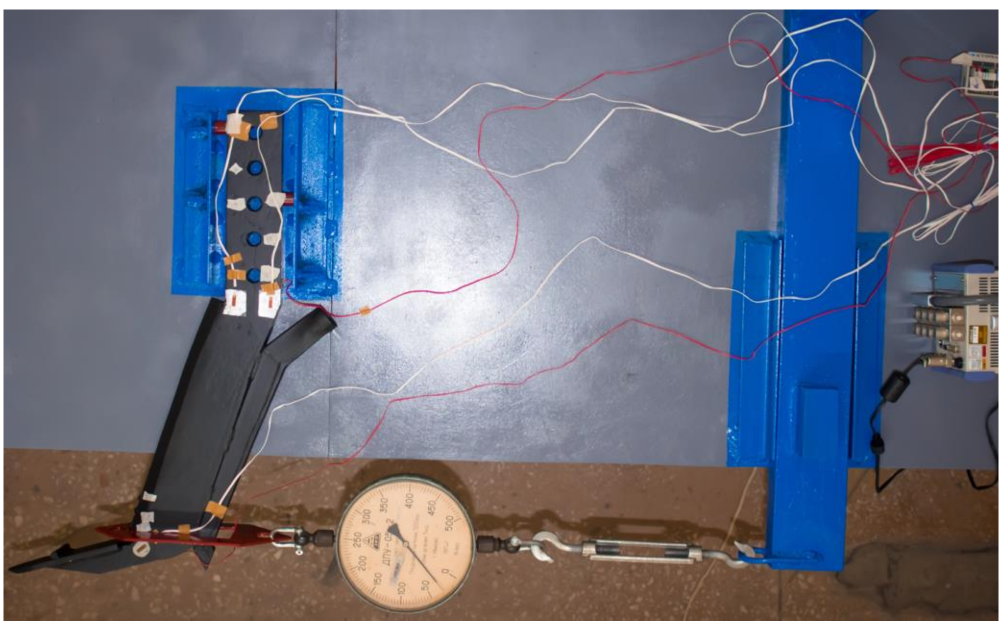


Figure 9. The fixed DPFA on the laboratory setup

By the FEM simulation software, the results were obtained, however, to simulate the static load and determine the strains induced on the DPFA in laboratory conditions, it was necessary to determine the centers of application of a resultant force depending on the different soil depths. A resultant force is a force acquired by combining a system of forces on a rigid body. The defining feature of a resultant force is that the resultant force has the same action on the rigid body as the initial system of forces (McCarthy, and Soh, 2010). Therefore, the assumption was accepted, that the soil resistance force applied to the DPFA is proportional to the front area of the DPFA. In this case, the method used to determine the centers of parallel forces on the DPFA, was the method of determining the gravity center of the rigid bodies. Thus, the front of the DPFA (the front area of the DPFA is perpendicular to the axis of soil movement) was divided into three geometric figures, symmetrical to the vertical axis. Figure 10 illustrates the scheme of the determined centers of a resultant force application depending on the different soil depths with all dimensions for calculation in mm.

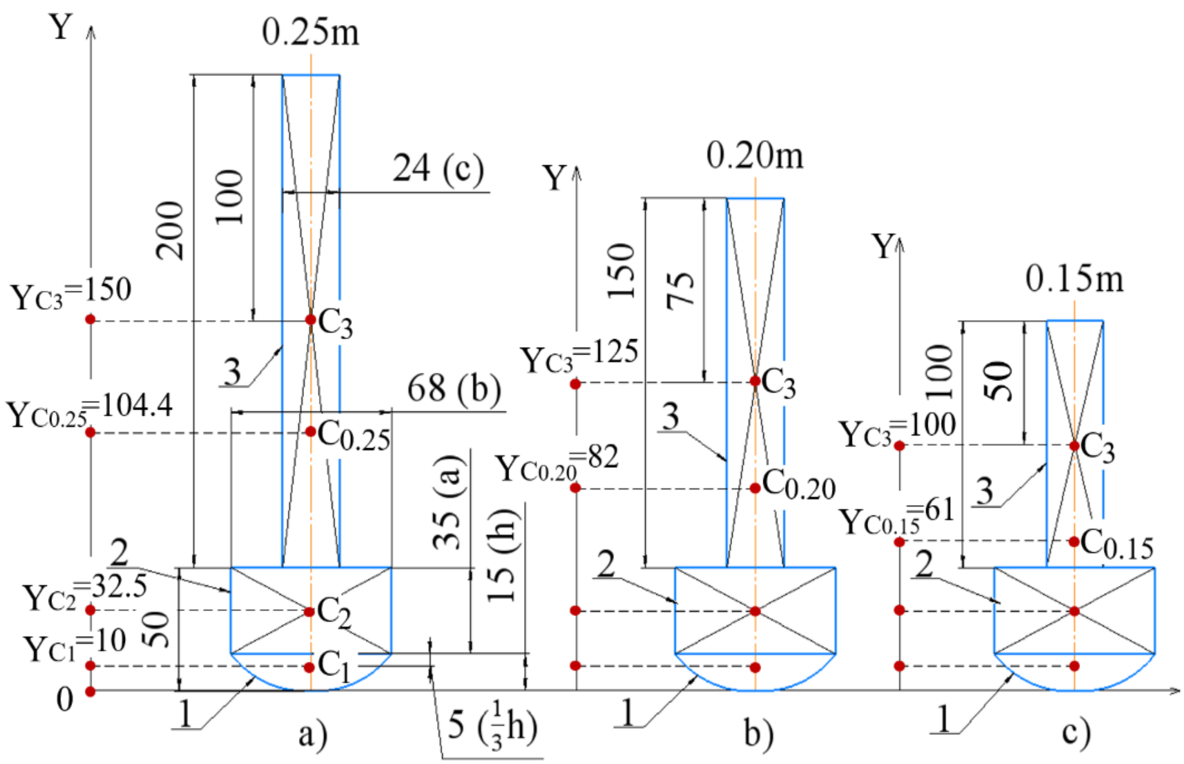


Figure 10. Scheme of a resultant force application depending on the different soil depths
1 – Triangle of the bottom knife part; 2 – Rectangle of the top knife part; 3 – Rectangle of the shank.

According to the scheme (Fig. 10), the coordinates of the centers C1, C2, C3 of the application of resistance forces of individual sections (1,2,3) of the DPFA, along the Oy axis as follows: C1 = 10; C2 = 32.5; C3 = 150 for soil depth of 0.25m were determined. Furthermore, C1 and C2 have constant values; however, C3 has a variable value, depending on the soil depth.

Subsequently, to determine the center of application for the resistance force on the DPFA, the formula for determining the center of parallel forces (center of gravity) was used (Lachuga, and Ksendzov, 2010), as follows:

$$Y_C = \frac{1}{S_{Total}} \sum \left(Y_{C_i} \cdot S_i \right) \quad (1)$$

Where: Y_C is the general center of application of the resistance force on the DPFA; S_{Total} is the total area of the DPFA (front area applied in the soil), mm^2; Yc_i are coordinates of the resistance force center of each DPFA areas, mm; Si is the area of each section of the DPFA, mm^2.

A brief example of the calculation for 0.25m applied force center is given below:

$$Y_{C_{0.25}} = \frac{Y_{C_1} \cdot S_1 + Y_{C_2} \cdot S_2 + Y_{C_3} \cdot S_3}{S_1 + S_2 + S_3} \quad (2)$$

Where: S_1=510 and S_2=2380 are areas of individual geometric shapes of the knife (Fig. 10 (1, 2)), mm^2; S_3=4800 is the area of the shank (Fig. 10 (3)), mm^2. However, according to figure 10 (b, c), the coordinate of the center resistance force will be changed, and the area S_3 (which is the rectangle of the shank) will be decreased.

$$Y_{C_{0.25}} = \frac{10 \cdot 510 + 32.5 \cdot 2380 + 150 \cdot 4800}{510 + 2380 + 4800} = 104.4 \text{ mm}$$

By the calculation, three applied force centers were obtained for the shank, and one center for the knife of the DPFA depending on the soil depth. Thus, for the laboratory experiment, we applied a static load on the force centers (Fig. 7 (3), Ch. 3) at a distance from the lower part of the DPFA ($Yc_{0.25}$=104.4 mm; $Yc_{0.20}$=82 mm; $Yc_{0.15}$=61 mm) for the shank, and (Y_k=28.5 mm) for the knife.

For conducting field experiments, it was planned to use the tractor model of MTZ - 82 (Four-wheel drive (4WD), traction class of 1.4 kN) for the developed seeder prototype with four DPFAs. Also, the seeder prototype is expected to have four DPFAs with a maximum depth of 0.25 m; therefore, the maximum resistance force (Rn) acting on one DPFA will be inversely proportional to the number of DPFAs. It follows that at the maximum operating depth of 0.25 m, the traction resistance of one applicator Rn can be determined as follows:

$$R_n = \frac{F_T}{n} \tag{3}$$

Where: F_T – traction class of tractor, кН; n – number of DPFA.

$$R_{25} = \frac{1.4}{4} = 0.35 \text{ kN}$$

However, the soil structure may have an uneven structure, which leads to an uneven distribution of the total loads on the DPFA; therefore, the calculated value of the resistance for the maximum depth will be R_{25} = 0.5 kN (rounded).

Hence, by using the laboratory configuration (Fig. 7 (3), Ch. 3), the static load of 5,000 N (0.5 kN) was applied with an interval of 500 N stepwise, and data recording was done manually. Three unique strain gage resistances were obtained depending on the simulation of different soil depths. Figures 11 and 12 show the results of obtained strain gage resistance by two different strain gages attached to the upper part of the shank (Fig. 8, zone 3) (as the most stressed loaded part of the DPFA). In addition, to confirm the accurate penetration angle of the DPFA (d=23) in the field experiments, the strain gages were attached to the down part of the shank (Fig. 8, knife zone 2). Figure 13 shows the laboratory results of obtained strain gage resistances of the down part of the shank (zone 2). The negative (–) direction of the strain gage's resistance shows that a foil strain gage deforms in the reverse direction.

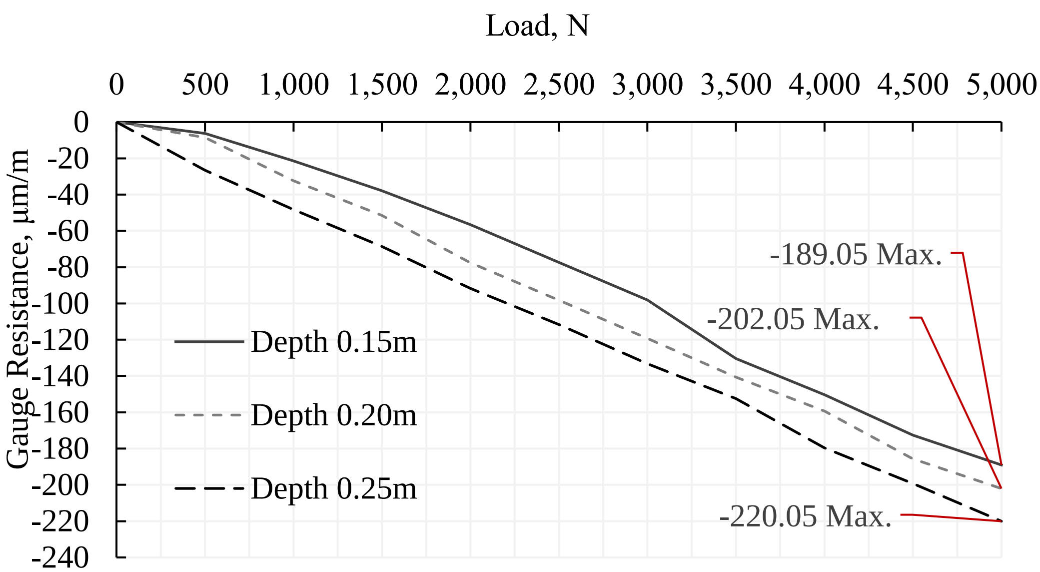


Figure 11. Strain gage resistance of KFGS-30-120-C1-11 L5M2R

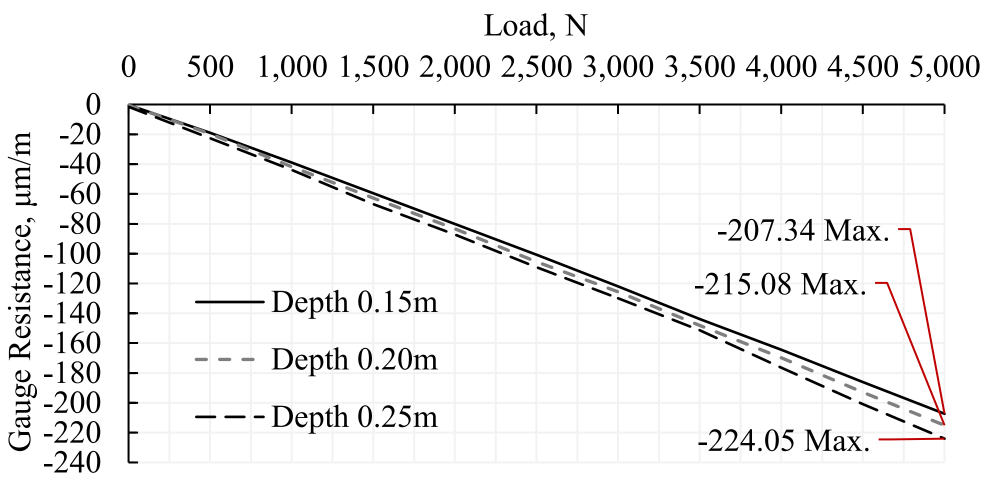


Figure 12. Strain gage resistance of KFGS-20-120-C1-11 L5M3R

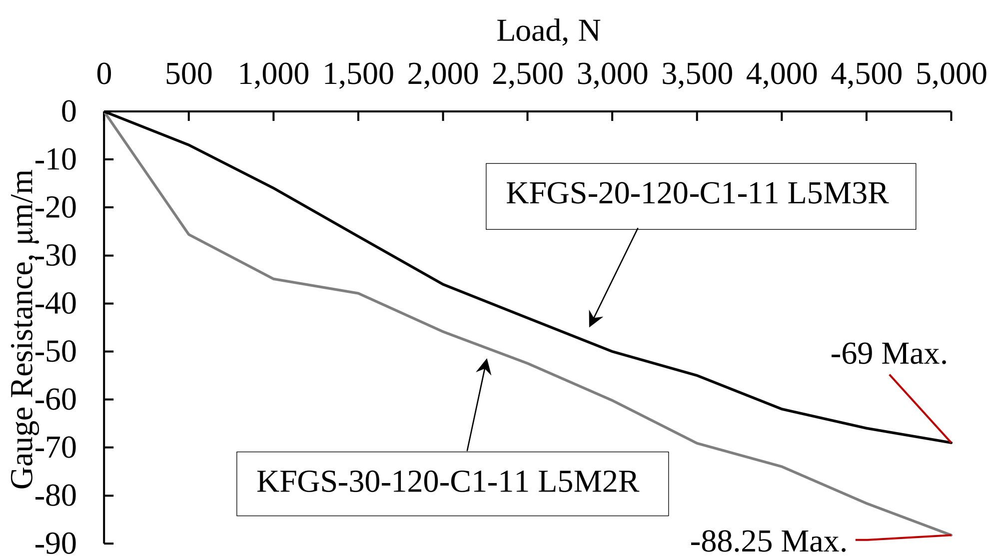
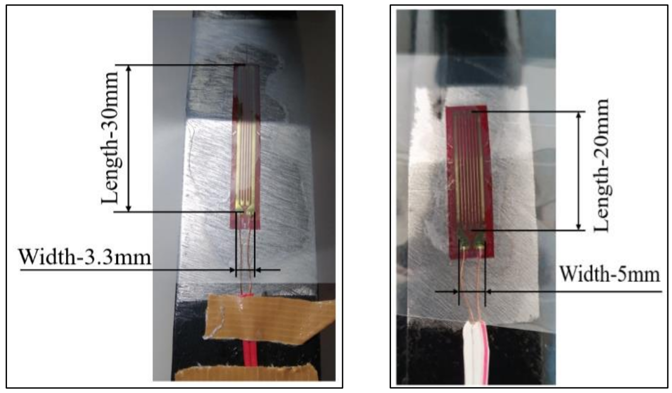


Figure 13. Strain gage resistance of the knife (Max. depth)

Moreover, it was noticed that there is an entirely different resistance sensitivity under the same experimental conditions, due to the different strain gage characteristics. Therefore, the strain gage with wider gage width (KFGS-20-120-C1-11 L5M3R) shows not a significant difference in the resistance between different simulation conditions. However, during the measurements, it was noticed that the KFGS-20-120-C1-11 L5M3R had fewer noises in comparison with the KFGS-30-120-C1-11 L5M2R which showed more stability in terms of data recording. These effects of noises can be explained by the different wire systems (WS) and connections between the strain gage and bridge box. Figure 14 illustrates the practical difference between the two strain gages (gage characteristics (Grid)) attached to the upper part of the shank of the DPFA.



a) b)

Figure 14. The work dimensions of used strain gages

a) – KFGS-30-120-C1-11 L5M2R (2-WS); b) – KFGS-20-120-C1-11 L5M3R (3-WS)

By the laboratory experiments, it was concluded that in order to capture more accurate strains induced by a load in a rigid body, it is preferable to use the strain gages with a longer gage length since it leads to obtaining accurate strains. Besides, the 3-wire gage connection system will avoid unnecessary noises and measurement errors. For further field experiments to calculate traction resistance of the DPFA and soil resistance induced on a subsoil area, consideration was taken by way of using the strain gages (KFGS-30-120-C1-11); however, with the 3-WS.

4.3 Seeder prototype development

According to Chapter 3 (3.4.2), the seeder prototype development was based on an SST model, therefore, it was conventional to assemble the DPFA to the main frame of the seeder and adjust the expected fertilizer and seeding rates. However, the frame construction was improved by the installation of connecting plates to fix the DPFA and enhance frame deflection characteristics. Therefore, the working width was reduced for the first prototype version. Moreover, seed hoppers were improved in order to allow the simultaneous sowing of soybean seeds and base fertilizers at the same depth by standard seed-feeding mechanisms (Fig. 4 – 6, App. 2 (detailed views)).

In addition, as mentioned above concerning developed machinery with DPFT, especially in Japan, the size and other technological issues are not suitable for Russian agriculture. Therefore, the best technological aspects were combined and developed for a new prototype. Figure 15 illustrates graphically the main principle of development.

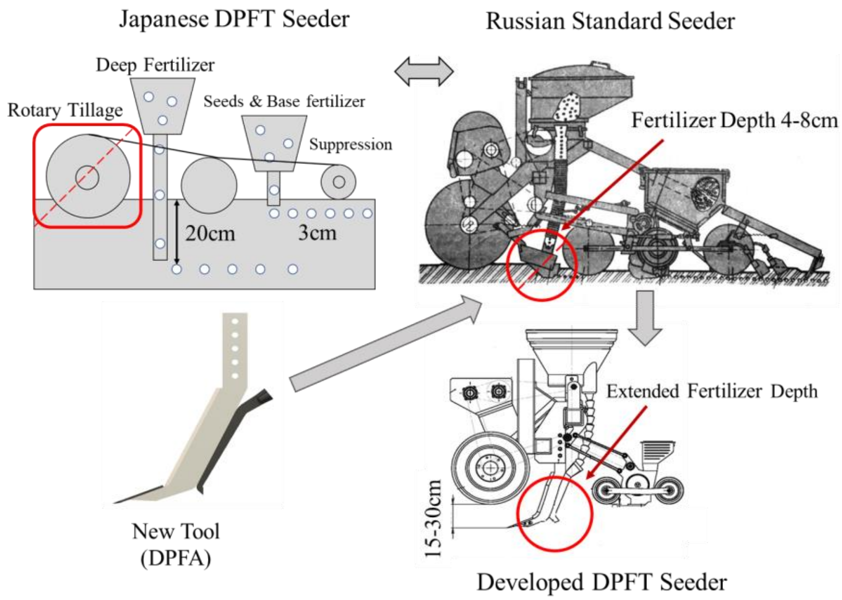


Figure 15. Key principle of prototype development

Figures 16 and 17 show a schematic diagram and overall view of the developed prototype, and in table 2 is given the prototype specifications.

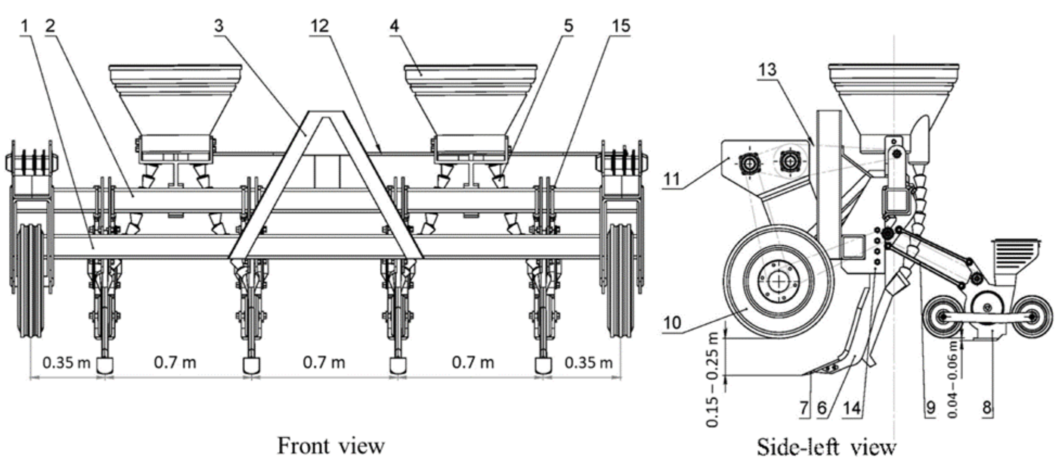


Figure 16. Schematic diagram of the prototype

1, 2 – lower and upper frame parts; 3 – hitch linkage; 4 – fertilizer hopper; 5 – fertilizer pipe; 6 – DPFA; 7 – DPFA's knife; 8 – seed-feeding mechanism; 9 – suspension; 10 – driving wheel; 11 – reduction gear; 12 – fertilizer hopper shaft; 13 – fertilizer hopper shaft drive chain; 14 – DPFA bolt connectors; 15 – frame parts connecting plate.

Figure 17. DPFT Seeder prototype (Side view), 2019

Table 2. Specifications of developed seeder prototype

Category, Unit	Range value
Operating speed, km/h	3.6 – 7.2
Working width, m	2.8
Row spacing, m	0.7
Seeding rate, pcs/m	8 – 35
Fertilizer rate, kg/ha*	30 – 150
Depth of seeds and fertilizers, m	0.04 – 0.06
Depth of deep fertilizers, m	0.15 – 0.25
Volume of seed, fertilizer hopper*, dm^3	95, 95
Volume of fertilizer hopper, dm^3	180 – 270
Required tractor power class, kN	1.4
Mass, kg	800

Note: * Seed hopper was adopted to have a section for base fertilizer application (Fig. 5, App. 2), therefore, the seed hopper volume was divided for two sections.

By this principal mechanical development of the conventional seeder of a Russian manufacturer, a new seeder prototype equipped with the DPFT was achieved and has mainly two features. First, this prototype provides subsoil tillage and deep application of slow-release fertilizers by the DPFA at depths of 0.15 – 0.25 m. Second, it performs simultaneous wide-row sowing of soybeans and application of base fertilizers at the same soybean sowing depths of 0.04 – 0.06 m. Consequently, this prototype is expected to be used in Russian agriculture, and allow plants to grow throughout the entire growing season by providing all-time nutrients.

4.4 Field experiments

The field experiments and practical use of the prototype were carried out at the experimental field of PSAA (43°52'11.1"N 131°56'04.9"E) by the determined experiment method (Fig. 10, Ch. 3). Thus, it was necessary to test the mechanical construction of the seeder prototype by a practical performance of the seeder prototype, and practicability of sowing soybean with deep fertilizer application by the results of soybean growth and development stages. Moreover, it was important to prove and verify practically the aspects of designed DPFA, especially in terms of deep fertilizer supply at the appropriate depths by the developed fertilizer pipes.

4.4.1 Practical use of the seeder prototype and DPFA

The main results and issues of practical use of the seeder prototype are presented as follows:

1) The soybean sowing (soybean and base fertilizer spacing) was satisfied by the seeder performance. The rage of the forward speed was from 0.8 to 1.6 m/s, with the seed spacing of 0.05 and 0.1 m. However, a sharp loosening of the soil row was noticed following the DPFA, with the formation of soil clods on the soil surface. Moreover, by increasing forward speed the number of clods on the soil surface increased significantly.

This was mostly the cause of deep subsoil loosening by the DPFA, which is the first tool in the sequence of developed technology (before seed-feeding mechanism), and physical soil properties, especially the soil moisture. However, the soil moisture during the field experiment (Saturday, June 1, 2019) varied from 15 – 25%. Thus, the significant quantity of clods affects the sowing in terms of a direct line of sowing seeds with an unpredictable seed spacing. Furthermore, the soil preparation before sowing also has a significant influence in terms of the smooth and even soil surface, which promotes to perform crop sowing with precision ratings and spacings. Figures 18 and 19 show the overview of the loosening of topsoil and the formation of clods by the DPFA, and actual distribution of soybean seeds.

Figure 18. Topsoil clods formation during the sowing

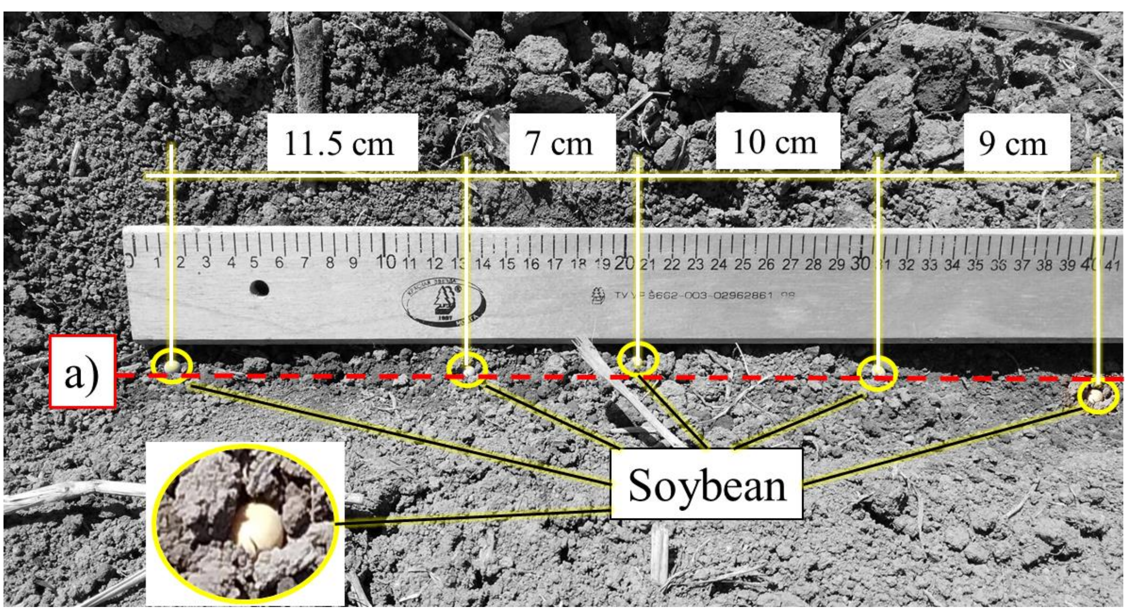


Figure 19. Actual distribution of soybean seeds

a) – Row line; Set seed spacing was 10 cm (0.1 m).

According to figure 19, the actual seed spacing was not satisfactory with the set seed spacing by the precision seed-feeding mechanism. The average difference was 2 – 3 cm from the settings. This uneven distribution of spacing will not meet the cultivation aspects in terms of developed technology, as it will affect soybean growth and development. However, the current seeder prototype model does the overall requirements in terms of soybean sowing combined by DPFT.

2) The performance of the designed DPFA in terms of subsoil tillage and deep fertilizer supply was met by the expected technological standpoints. However, some practical issues were noticed during the experiments, as follows:

- The DPFA increases the tractive resistance due to the massive size, especially the knife area, and increases the total draft force, particularly at a depth of 0.25 m. Moreover, it was noticed higher soil stickiness at a depth of 0.20 and 0.25 m, due to high clay contents. It was noted that when the DPFAs were installed at a maximum depth of 0.25 m, the tractor' wheels slipped on the 4WD at a forward speed of 1 – 1.6 m/s. This event indirectly indicates that at the maximum depth of 0.25 m, the maximum potential of the tractor's traction class is used. Thus, the total draft force seeks to increase upon the tractor traction class (1.4 kN). Therefore, the DPFA shape needs to be improved in order to meet better performance standards in accordance with an optimum traction tractor class.
- The outlets of the fertilizer pipes were blocked periodically by the clay soil at the depths of 0.20 – 0.25 m. Therefore, it was difficult to maintain control of the deep fertilizer supply. Thus, the DPFA shape required to be improved by an additional set up of hoes, such as small weed knives to the outlet area, in order to form an extra canal and protect the fertilizer pipe outlet.

Consequently, these issues have one of the most important features and have a significant impact on the characteristics of the prototype seeder and its performance. Therefore, in further solutions, it is critical to consider these factors, especially in optimizing DPFA shapes. Besides, the current DPFA model performs the set requirements in terms of subsoil cultivation and seed fertilizer application. In figures 20 and 21 are given some examples on the soil sticking to surfaces of the DPFA and booked fertilizer pipes. Moreover, figure 22 shows the applied deep fertilizers at maximum depth.

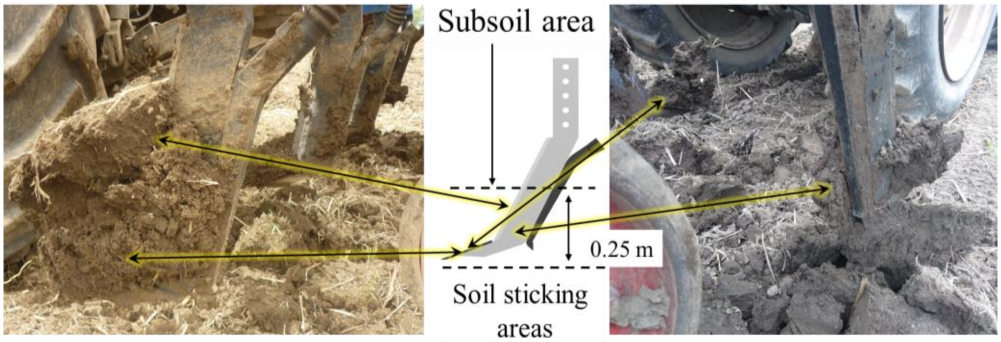


Figure 20. Soil sticking views at the DPFA

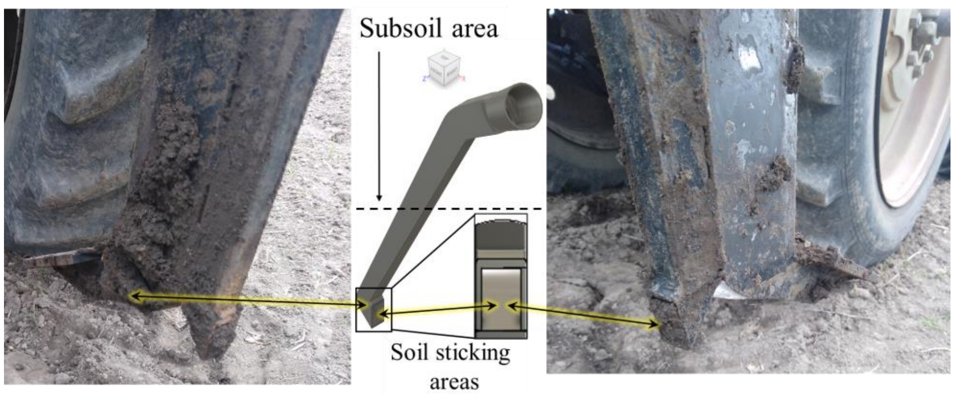


Figure 21. Blocked outlet of the fertilizer pipe

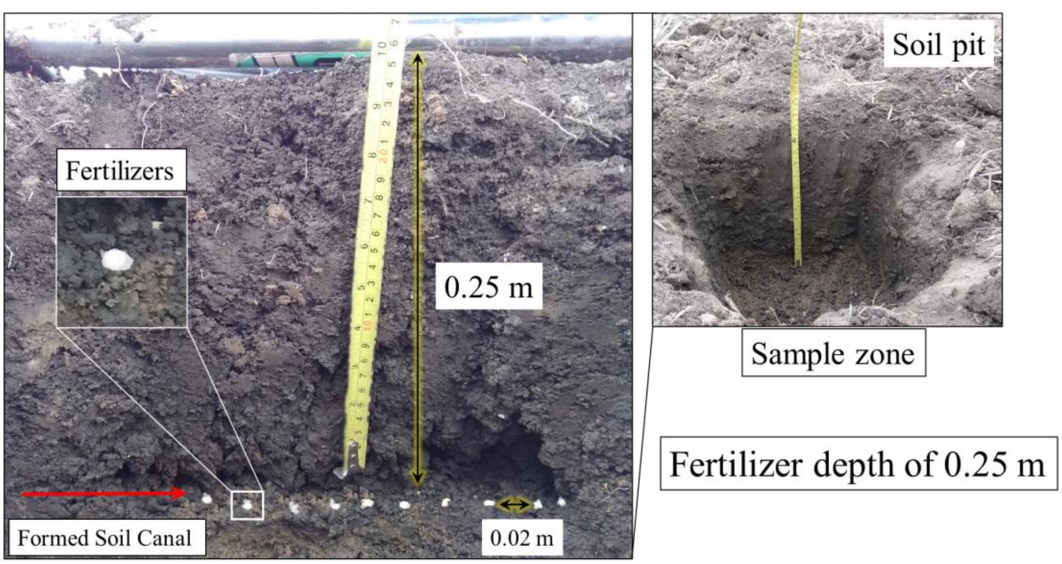


Figure 22. Sample of deep fertilizer supply

According to figures 20 and 21, there is an issue with the impact of the soil sticking effect to the front area of the DPFA as well as the area of the fertilizer pipe outlet. However, according to the soil pit sample (Fig. 22), the DPFA performs the subsoil tillage of compacted soil layers properly and forms a canal leading to air and water exchange, as well as fertilizer application. Moreover, the fertilizer spacing is performed accurately by the standard fertilizer-feeding mechanism placed in the fertilizer hopper, and it has a precision rate with an average spacing of 0.02 m between granulated fertilizers.

4.4.2 Soil resistance measurements

Due to a lack of data and valid studies on draft force and soil resistance properties such as soil compactness and assumptions related to soil moisture in PK, Russia, field experiments were conducted. Consequently, the soil resistance measurement experiments were conducted to verify the FEM simulation and laboratory experiments and obtain data on draft forces induced by the DPFA, as well as soil resistance. Figures 23 and 24 show the summarized dynamic results of three replicate experiments (three times measurement) on soil resistance induced on the DPFA at the different operating depths.

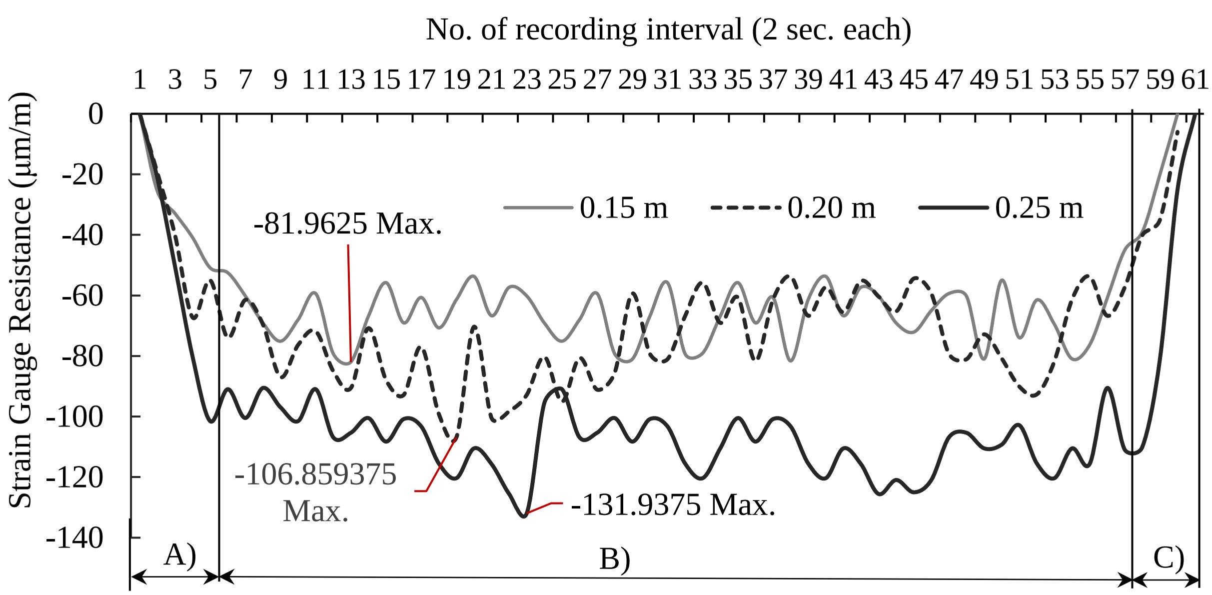


Figure 23. Dynamic strain gage resistance results induced on the knife

A) – Deepening; B) – Main operating time; C) – Lifting.

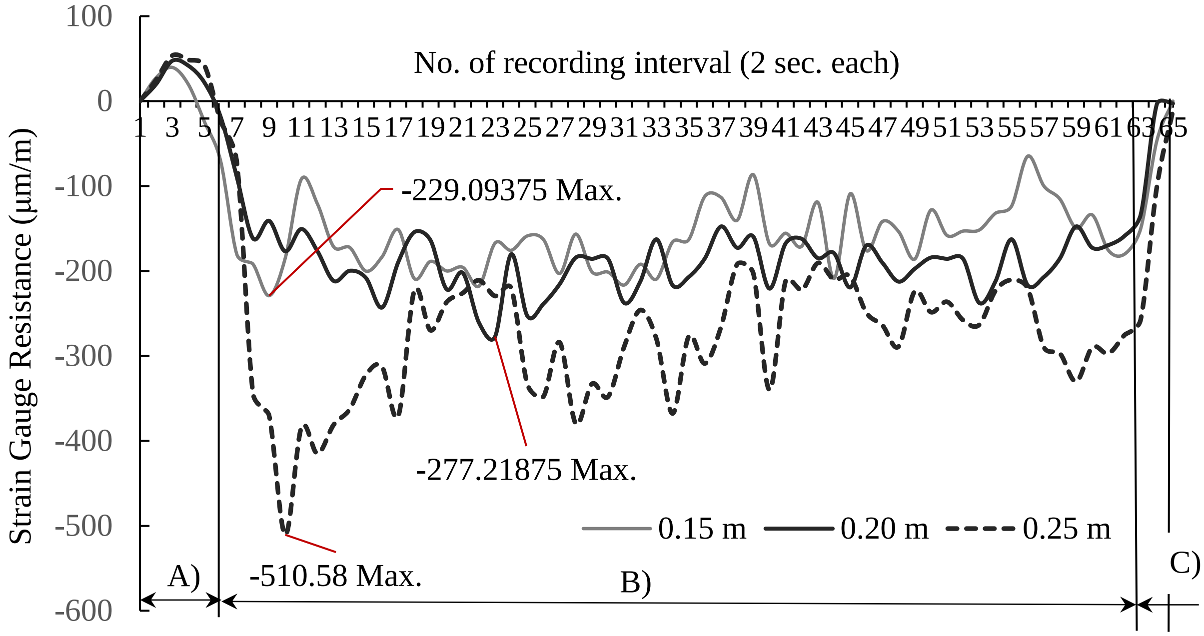


Figure 24. Dynamic strain gage resistance results induced on the DPFA (Total)
A) – Deepening; B) – Main operating time; C) – Lifting.

According to figure 23, the maximum dynamic resistance of -131.9 μm/m reaches at 0.25 m depth, which is over the maximum resistance of -88.25 μm/m at a load of 5,000 N, which was obtained by the laboratory experiments. However, since the strain resistance increases linearly, with the average interval of -9 μm/m (Lab. experiments), the dynamic resistance can be converted to appropriate values according to the data obtained by field experiments. Thus, it can be concluded that at the field experiments, the maximum dynamic force of a 0.25 m depth induced on the knife part of the DPFA reaches up to 7,400 N. However, the average dynamic resistance shows -100.1 μm/m, which is equivalent to 5,650 N force. In addition, the average dynamic resistance of 0.15 and 0.20 m depths show -59.8 and -68.48 μm/m, which is equivalent to 3,330 and 3,800 N force, respectively. Moreover, during the main operating time (Fig. 23, B)) the most stable soil resistant force can be seen at depths of 0.15 and 0.20 m since these depths are lying before the main clay layers.

The findings of the total dynamic resistance induced on the DPFA results showed the total subsoil force met during three different depths. According to figure 24, the maximum dynamic resistance of -510.58 μm/m (12,200 N) reaches at 0.25 m depth, which is practically more than double of the expected force obtained by the laboratory experiment. However, this pick is observed only temporary, and during the main operating time the average resistance reaches -273.6, which is equivalent to 6,325 N force per one DPFA. Furthermore, the average dynamic resistance of 0.15 and 0.20 m depths show -153.4 and -181.009 μm/m, which is equivalent to 3,835 and 4,525 N force, respectively. Moreover, it was noticed that the tractor' wheels slipped by 4WD at the maximum depth of 0.25 m, during the beginning of the deepening of the DPFA (Fig. 24, A)) and the main operating time (Fig. 24, B)). This indicates that at the maximum depth, the maximum potential of the tractor's traction class was overused, and the average graft force was 25.3 kN (25,300 N), which is more than 18 times of the tractor traction class (1.4 kN). Therefore, the current shape of the DPFA has not met the requirements in terms of the tractor traction class. Thus, the current DPFA shape needs to be improved in further steps of the study to meet improved performance in accordance with an optimum traction tractor class.

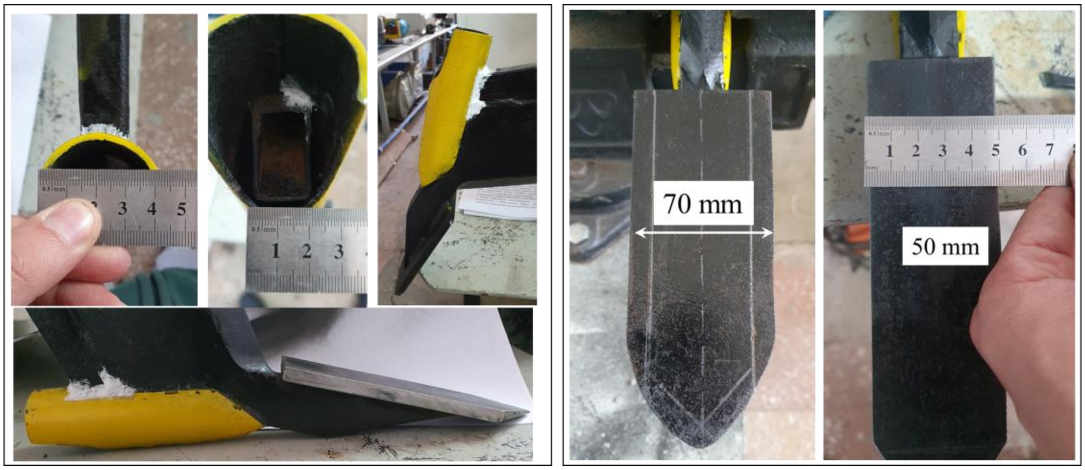
4.4.3 Practical solutions

According to the experiment results on soil resistance measurements, there arose issues with soil sticking to the front of the area of the DPFA (increased total resistance), as well as the area of the fertilizer pipe outlet (blocked fertilizer pipe outlets), several practical solutions were done in order to solve these issues.

The main purposes of practical solutions were to carry out several experiments by improved DPFAs. The first purpose was to verify the soil resistance sensitivity on a reduced knife width (the max. loaded knife area) of the DPFA in order to decrease the total draft force. Second, to solve the issue with soil blocking of the outlet of the fertilizer pipes by an additional set up (implements) to the outlet area of the DPFA to form an extra fertilizer canal and protect it from soil blocks. Therefore, three types of protective implements for the DPFA were made to solve this issue with the fertilizer outlets, and one version of the DPFA with a reduced width area of the knife.

The total knife width (Fig. 1, (k =68 (± 2) mm)) was reduced by 20 mm in order to verify the influence of the knife width upon the soil resistance. Furthermore, the experiment was performed at the 0.25 m depth, and the result was compared with non-improved (control) DPFA. Moreover, three protective implements with different shapes were attached to the DPFAs.

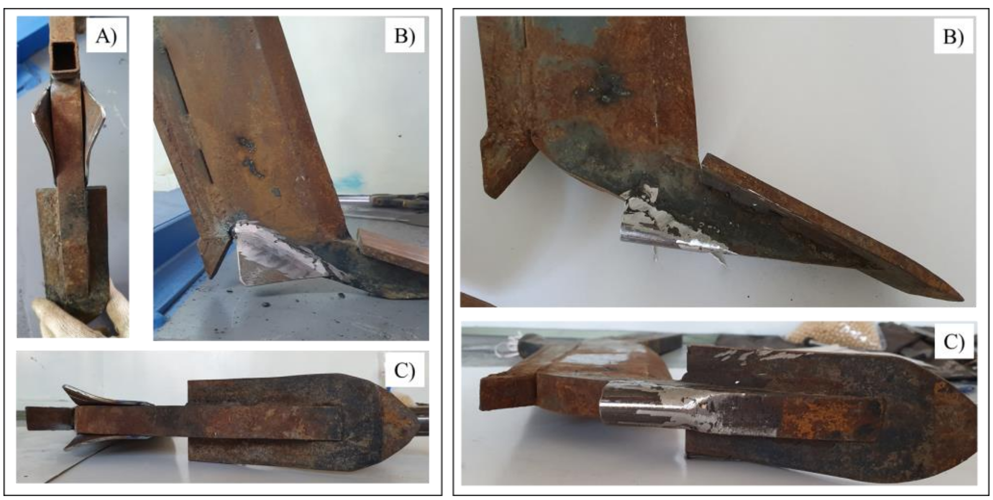
Figures 25 – 26 show the overview of the made solutions, and in appendix 2 (Fig. 7) is given an overview of the improved DPFAs in comparison.



a) b)

Figure 25. The first option of the improved DPFA

a) – Shape of the fertilizer outlet protection (Cylinder-shaped type); b) – Reduced knife width.



a) b)

Figure 26. The second and third options of the improved DPFA

a) – Hoes (Weed knives type); b) – Plate type.

A) – Back view; B) – Side view; C) – Bottom view.

The new field experiment was carried out fall season (Thursday, Oct. 24, 2019) after soybean was harvested, however, the experimental field was prepared by harrowing the depth of 0.15 m. Since the experiments were carried out in the fall season (different time from the first field experiments), it was not appropriate to compare the previous dynamic strain resistance results (Fig. 24) with the new strain resistance results. The main reason was that the soil has a different compacted structure with different moisture contents. Therefore, the actual strain resistance was correlated with different shapes of the improved DPFA. Consequently, figure 27 shows the results of the performed field experiment of 0.25 m depth. Additionally, in appendix 2, figure 8 is given the overall result of 0.20 m depth by comparison of improved DPFAs, in order to confirm the significance between the different types.

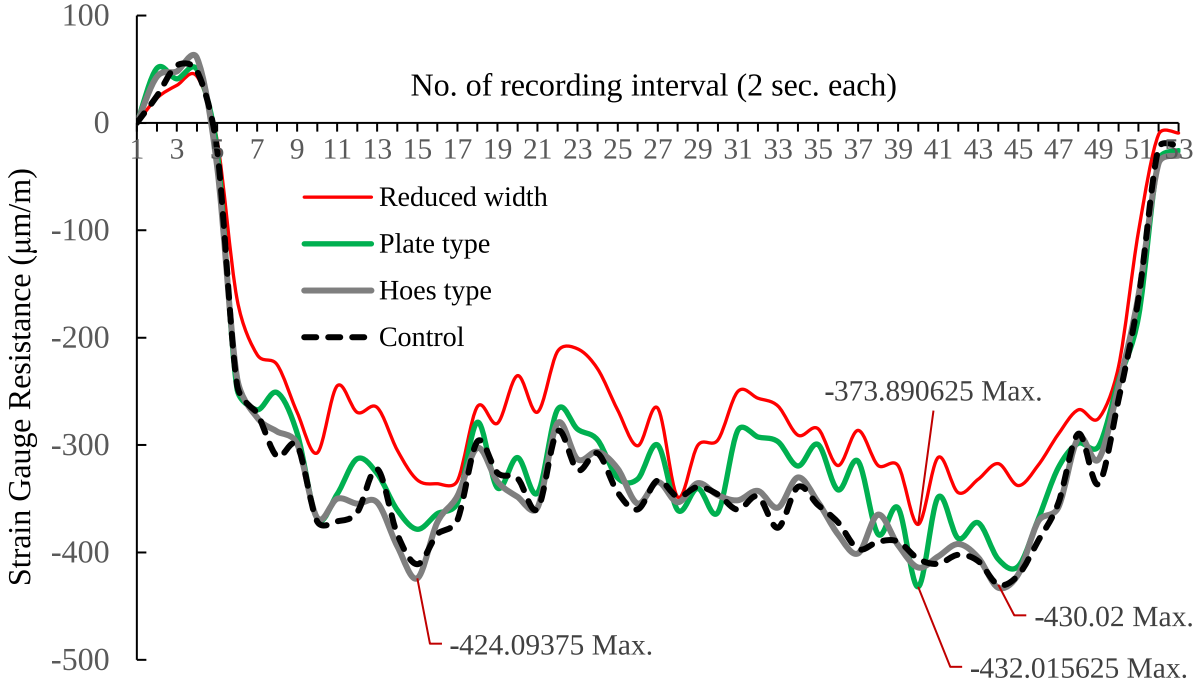


Figure 27. Strain resistance in a field experiment of improved DPFAs (Total)

According to figure 27, the DPFA with the reduced width (Cylinder-shaped type) showed the best results in terms of a reduction of the soil resistance compared to other types of DPFAs. The maximum strain gage resistance was -373.8 µm/m (8,447 N) with the average value during the operating time of -240.8 µm/m (5,466 N). The average strain gage resistance of the Plate type, Hoes type and Control (non- improved) DPFAs showed similar value of -281.46, -297.96, and -300.69 µm/m (6,387, 6,763, and 6,825 N), respectively. Therefore, it can be concluded that the front area of the DPFA has the most significant characteristic in terms of the total draft force, which was an obvious fact regarding soil resistance induced as an agricultural tool. By the decreased knife width by 20 mm, the induced subsoil force was decreased by 20% (5,466 N) in comparison with the control DPFA (6,825 N), thus, the optimum front area of the DPFA should be considered in further shape optimizations. Moreover, it can be noted that the Hoes type DPFA did not have a significant value in terms of increasing the total strain resistance by the hoes implements.

The experiment of the fertilizer transportation, canal formation, and protection of the outlets from soil blocks also showed an important result. Figures 28 and 29 illustrate some main aspects of the experiments.

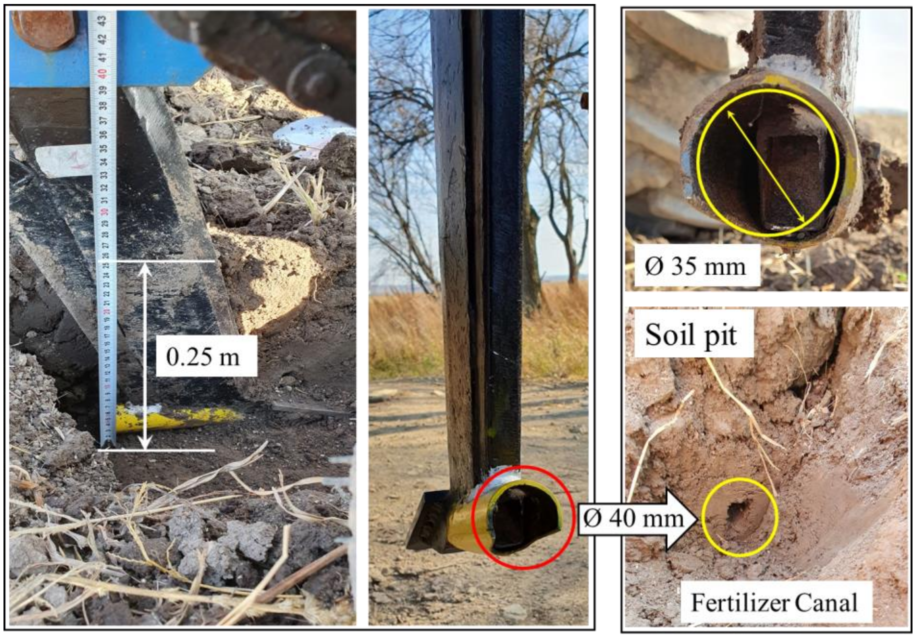


Figure 28. Cylinder-shaped type DPFA

Figure 29. Plate and Hoes types DPFAs

According to figure 28, the DPFA with the cylinder-shaped type showed perfect results in canal making for the fertilizer supply. Moreover, it has been proven that it forms a round canal which prevents blocking the fertilizer outlets (Fig. 28, soil pit). However, there is still a risk of soil sticking to the outlet area, especially in the lifting of the seeder after the main operating time. In appendix 2, figure 9, there is an example of the soil sticking to the outlet area of the fertilizer pipe.

In addition, the Plate type DPFA did not show any significant results in terms of the fertilizer outlet protection. It was noticed that the plate which was made on the down part of the DPFA (chisel shank) had no impact on the line-canal shape inside the soil. However, the Hoes type DPFA showed significant results in terms of the fertilizer outlet protection and additional subsoil cultivation. It was concluded that the hoes attached to the side down part of the DPFA has the effect in the shape of a fertilizer canal by expanding the soil. Plus, this DPFA type did not increase the strain resistance, and had almost similar value as the control implement. Moreover, the blocking of the fertilizer outlets was not noticeable during all field experiments. Therefore, the hoes type DPFA, in accordance to the DPFA with the reduced width value might be considered as the main implement in further development.

In the conclusion of the subchapters of 4.4.2 and 4.4.3, it can be said that the front area of the DPFA, as well as the penetration angle, have the most significant value in soil resistance upon total draft force, particularly in heavy clay soil. Therefore, the current DPFA shape should be improved by way of streamline design, which would significantly reduce the amount of used material and the final cost. Moreover, according to the data (practical force) obtained by the experiments, a new draft graphic simulation was conducted to determine the actual load distribution inside the DPFA body (Fig. 10, App. 2). The simulation results that only 30% (average) of the total material mass DPFA has the most loaded structure, and by proper way of streamline design the total mass can be optimized up to 40 – 60% of the current shape. Consequently, by the streamlined design, the total mass, as well as the front area of the DPFA, and the total soil resistance will be decreased up to 50 – 60% toward meeting the traction class for maximum operating performance.

4.4.4 Soybean growth and development

In the introduction of the DPFT in PK, many farmers are interested in the economic yield of soybean by this relatively new technology. Thus, it was essential to determine the productivity of soybean plants to prove its profit from the standpoint of better soybean yield and quality. Therefore, during this study, a range of phenological observations of plants from the standpoint of its development and determining the productivity per one plant from the standpoint of overall yield have been done.

Since this PhD study was conducted during 2017 – 2019, and the field experiments were performed in two seasons (2018 – 2019). In addition, in order to conduct properly the plant and roots development observation, it was necessary to have numerical data to evaluate plant height, root length, and soybean yield by using a statistical method via box-whisker plot to display variation in samples of a statistical population to know the statistical relationship (Tukey, 1977). In this case of data gathering, it was important to use box-plant plots to observe accurately plant development. However, in 2018 due to unsatisfactory weather conditions, more than 70% of plants were destroyed by floodwater, and it was not possible to collect any valuable data on soybean plants. Therefore, in the season of 2019, the overall phenological observations were done without box-plant plots due to the limitation of time and study equipment. Thus, to complete field experiments and evaluate overall the use of DPFT, a range of possible observations was conducted.

The experiments on soybean growth and development were carried out during the vegetative (VC) and reproductive (R 1 – 6) stages. The experiment on soybean yield (determining the productivity per one plant) of 10 random plants was carried out at the stage of R6, and at the stage of R8 (after harvesting) the mass of seeds was recorded.

According to the results of the phenological observations, it should be noted that in the phases of complete shoots (VC stage) at the control plot, plants reached a depth of 7.6 and 7.5 cm by the seed spacing of 0.05 and 0.1 m, respectively. From a fertilizer depth of 0.15 m, they reached a depth of 7.8 and 7.5 cm, which was increased by 2 and 0%, respectively, compared with the control plot result. At the fertilizer depth of 0.2 m, the plants reached a depth of 8.4 and 8.1 cm, which was an increase of 10 and 8.5% compared with the control plot, respectively. Moreover, at the fertilizer depth of 0.25 m, they reached a depth of 9.8 and 10.2 cm which was increased by 29 and 36%, respectively.

At the stage of the trifoliolate leaves (V1) in the control plot, the depth of the roots was 9 and 9.5 cm by the seed spacing of 5 and 10 cm, respectively. At the fertilizer depth of 0.15 m, the roots germination depth was 11.5 and 12 cm (increased by 27 and 26%, respectively). The fertilizer depth of 0.2 m showed that the depth of the roots was 12 cm, which was an increase of 33, and 26%, respectively; and the fertilizer depth of 0.25 m showed the root depth of 11.5 and 12.5 cm (27 and 32% compared to the control plot).

At the beginning of stage R3 (bean (pods) formation) in the control plot, the root system depth was 17 and 17.5 cm, respectively. At the fertilizer depth of 0.15 m, the root depth was 18 and 18.5 cm (6% more to the control plot). At the fertilizer depths of 0.2 and 0.25 m, the root depths were 20 and 21 cm (18 and 20% increased). Figures 30 – 33 shows several results of the general view of soybean plant observation.

a) b)

Figure 30. Growth stage V1, 22 June 2019

h – Fertilizer depth; P – seed spacing, 5 cm.

a) – Without DPFA (Plant height – 20 cm);

b) – DPFT 0.25 m (Plant height – 28cm, more developed Plant)

a) b)

Figure 31. Growth stage R3, 8 August 2019

h – Fertilizer depth; P – seed spacing, 10 cm.

a) – Without DPFA (Plant height – 35 cm);

b) – DPFT 0.25 m (Plant height – 45 cm, more developed Plant)

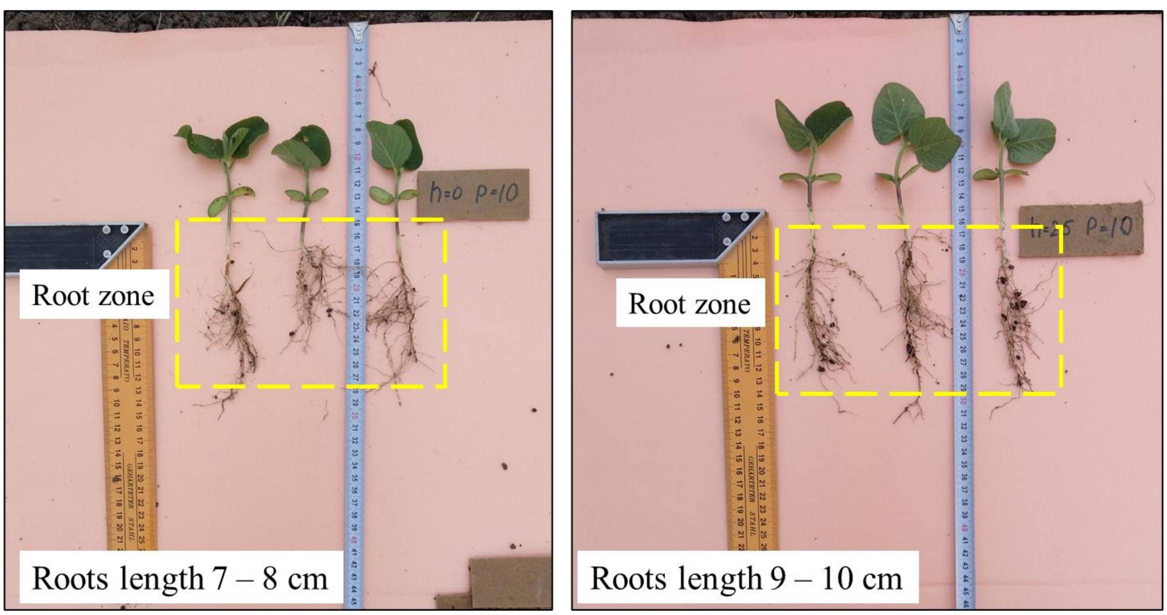


Figure 32. Growth stage VC, 7 June 2019

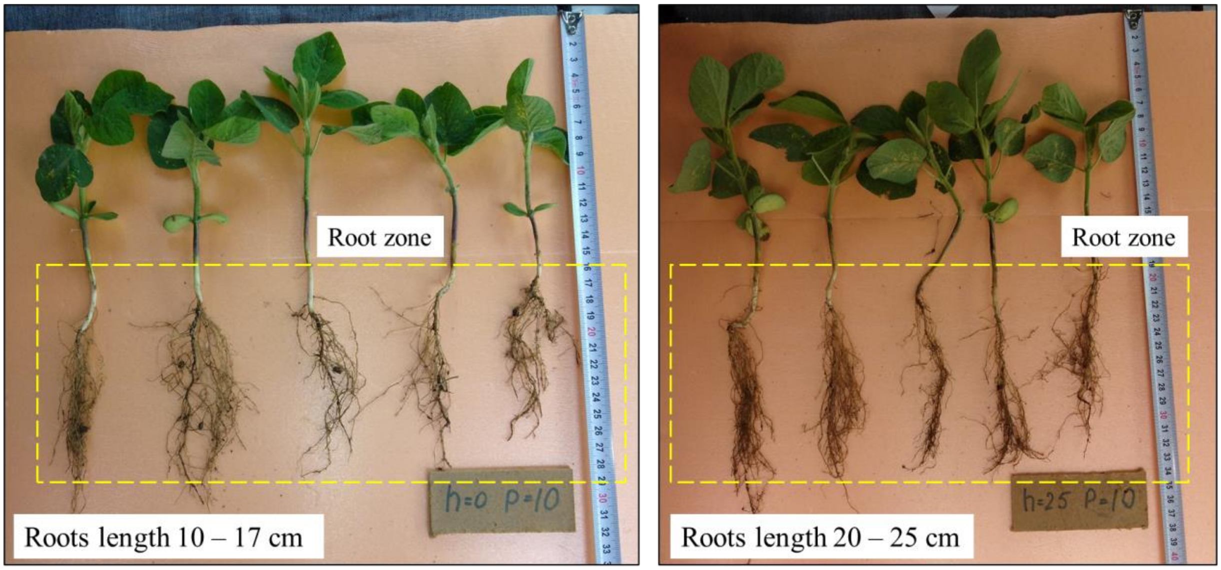


Figure 33. Growth stage V1, 22 June 2019

Consequently, it should be noted that at the growth stages of V1, the main part of the root system did not reach the depth of fertilizer application. However, it was found that the main part of the root system reaches the fertilizer application depth of 15 – 20 cm at the stages of R1 – R3 (time of the flowering and bean formation). Thus, the fertilizer application depth of 15 – 20 cm can be considered as the most favorable. Furthermore, the overall results have proven once again the study findings completed by Japanese experts (Takahashi et al., 1991; Tewari et al., 2005; Kaushal et al., 2006; Ohyama et al., 2010), as well as from Bangladesh and China (Liu et al., 2015; Gaihre et al., 2016; Mazid et al., 2016). Moreover, it was found that the root system of the plants develops more intensively by DPFT compared with the control plot. However, to prove fertilizer influents (as its amount per plant) on the root system's distribution (root design in heavy clay soil), fundamental studies are needed to know any further progressions in root development.

The data on soybean yield is graphically estimated in figure 34, and numerical data is summarized in tables 1 – 5 (App. 3). Moreover, the used seed and fertilizer rates are introduced in appendix 3. Furthermore, the DPFT results were compared with a conventional planting method (Row spacing 15 cm), which is currently and widely used in PK, Russia.

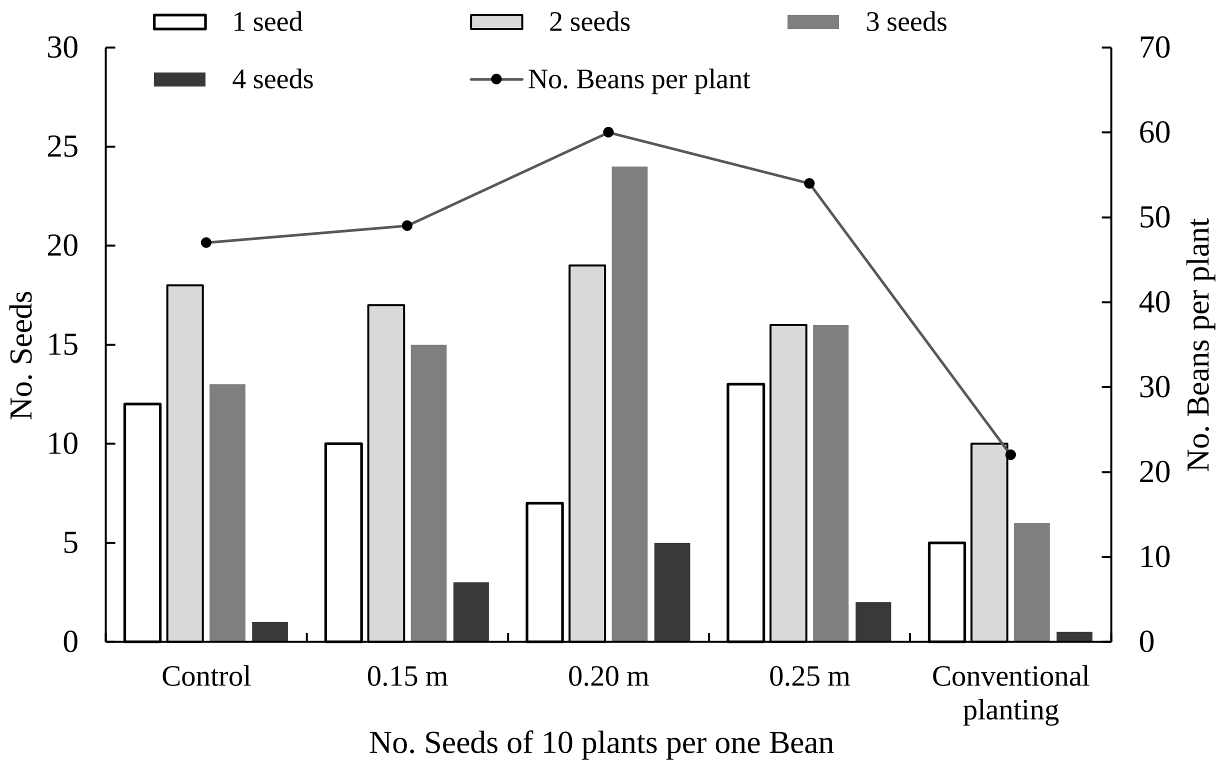


Figure 34. Soybean yields by different cultivation methods, 2019

Figure 34 represents the average number of seeds per different type of beans (pods) estimated from 10 plants. Moreover, there is an average value of total beans per one plant. Additionally, the yield result of the conventional planting method shows us the practical advantages of the DPFA. Figures 35 and 36 show the differences between the same varieties of plants and the number of beans by the DPFT and the conventional planting method.

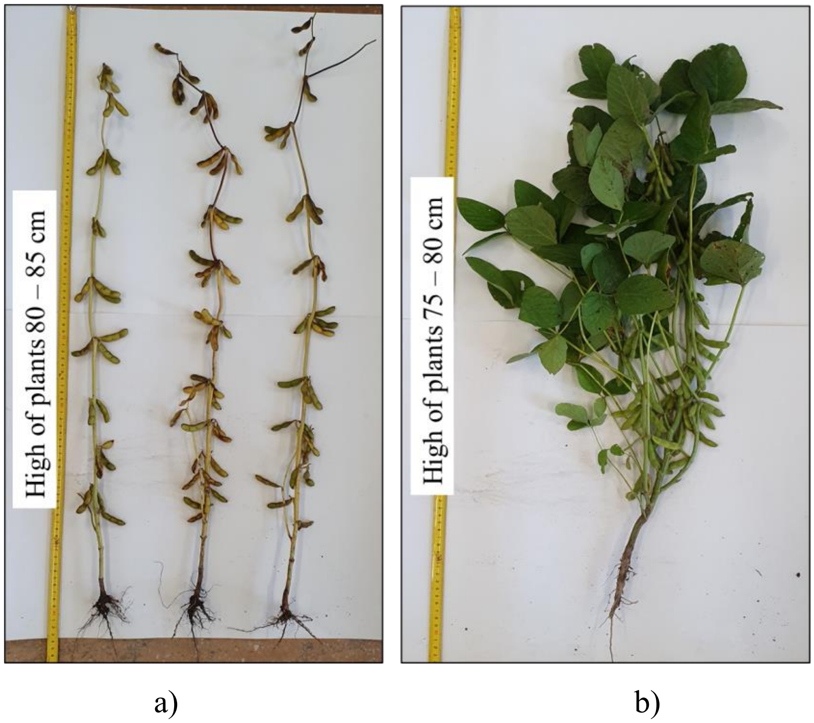


Figure 35. Soybean plants by different cultivation techniques, 9 September 2019

a) – Conventional planting, stage of R8; b) – DPFT, stage of R6 (0.2 m)

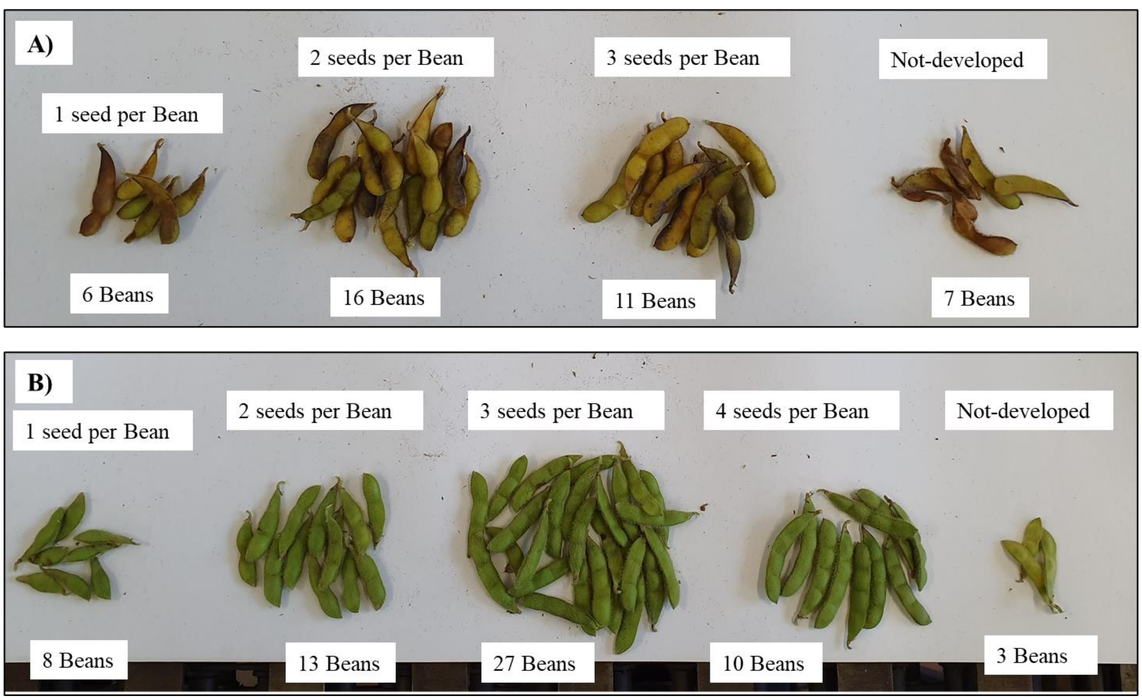


Figure 36. Number of beans, 9 September 2019

A) – Conventional planting; B) – DPFT (0.2 m)

According to the phenological observations and yield results (Fig. 34), we can conclude that the best results of soybean in terms of yields and root development is the application of the DPFT with the depth of 0.2 m. Moreover, link to the soil resistance results, it was found that at the depth of 0.2 m (before heavy clay soil), the seeder prototype meets the tractor traction class, and with further development of shape and optimization of the DPFA, the working width of the prototype may be extended in order to meet greater expectation through better performance. However, deep fundamental research on fertilizer rates and roots development, as well as newly developed DPFA are needed to be conducted for the verification of greater results plant depths on-site within PK, Russia.

4.5 Conclusions

The design of the DPFA with the optimum material properties and required safety factors for soybean cultivation was obtained by the FEM simulation, and the DPFA prototype model was manufactured for the laboratory simulation and field experiments. The results of the field experiments showed the actual soil force which was induced on the DPFA had an overload ranging from 50 to 120% of the applied force in the simulation, which had significant influence on a tractor traction class. However, by the practical solutions with experiments, the way of further development for the current DPFA model has been confirmed. Furthermore, the practical use of the seeder prototype with DPFT for soybean sowing was satisfied by the seeder performance at the range of forward speed 0.8 to 1.6 m/s. However, some technical issues should be improved to generate better operating performances.

The results of soybean growth and development have shown that the best soybean yield, growth, and development was principally obtained by the DPFT application depth of 0.2 m. Moreover, at the depth of 0.2 m, the seeder prototype met the tractor traction class, as well as the fertilizer application depth of 15 – 20 cm which can be considered as the most promising for soybean planting in PK of Russia. Furthermore, all performed experiments have obtained exclusive practical data on the practicability of a developed and improved Russian manufactured seeder (modelled after a DPFT), especially on soil resistance force, soybean growth and development of DPFT, since this type of study has never been done before. Therefore, this study has a huge potential for further practical development.

CHAPTER 5

SUMMARY AND CONCLUSIONS

This Ph.D. research was aimed at investigating the practicability of a developed Russian manufactured seeder by using a DPFT as a model, toward enhancing potential crop production in Primorsky Krai (PK), Far East of Russia. The fundamental purpose of this study was to achieve a future cost-effective model on the country's market, which could be equivalent to more expensive competitors on the global machinery market, and meeting high-performance necessities which could be practically realized for soybean cultivation in PK.

The study findings showed that the agricultural mechanization in PK had not been developed yet to its full potential, and newly developed agricultural equipment was needed for its development. The current situation of agricultural mechanization was described based on the information gathered from the Statistics Office of the Russian Federation, scientific articles published in Russia, and own observations. However, the perspectives of agricultural mechanization that were obtained showed various directions for improving agricultural mechanization and productivity. Especially, in terms of systematic data collection to always have a clear perspective on agricultural productivity, machinery use, and logistical information for managing agricultural mechanization.

The design of the new DPFA has been done for the optimum material selection and obtaining the required safety factors for subsoil cultivation, and its fertilizer pipe transporting fertilizers into deep soil layers. Three different applied forces in the FEM simulation of 4,500, 5,000, and 6,000 N were considered for three different application fertilizer depths of 0.15, 0.20, and 0.25 m. The best-selected material property for the DPFA manufacture was the AISI 4135 QT carbon steel plating with the high yield strength of 780 MPa and ultimate tensile strength of 950 MPa, Young's Modulus of 207 GPa and with Poisson's Ratio of 0.33, which led to having a total mass of 11.78kg of the DPFA. However, further development of the DPFA shape should be considered by way of streamline design, and soil sticking issues, particularly to the fertilizer pipe outlets.

The practical use of the developed DPFT seeder prototype for soybean sowing was satisfied by the prototype performance at the range of a tractor's forward speed of 0.8 to 1.6 m/s. Moreover, the labor-saving issue was achieved by the performance of deep tillage and simultaneous deep placement fertilizer application.

The findings of the total dynamic resistance induced on the DPFA results showed that the maximum force of 12,200 N was reached at a depth of 0.25 m, which was practically more than double of the expected force. However, this pick was observed only temporarily, and the average force reaches 6,325 N per one DPFA. Furthermore, the average dynamic force of 0.15 and 0.20 m depths showed a 3,835 and 4,525 N force, respectively. Therefore, the current DPFA shape needs to be improved in the progression of future research to meet better performances following an optimum traction tractor class.

The results of soybean growth and development have shown that the best soybean yield, growth, and development was principally obtained by the DPFT application depth of 0.2 m. As a result, it should be noted that at the growth stage of V1, the main part of the root system did not reach the depth of fertilizer application. However, it was found that the main part of the root system reaches the fertilizer application depth of 15 – 20 cm at the stages of R1 – R3 (time of the flowering and bean formation). Thus, the fertilizer application depth of 15 – 20 cm can be considered as the most promising for utilizing this technology in PK. Additionally, according to the soil resistance results, it was found that at a depth of 0.2 m (before heavy clay soil), the seeder prototype meets the tractor traction class, after the reduction (improvement) of the total width of the DPFA knife, and the working width of the prototype may be extended to prove this technology in large scale agriculture. However, new weed control technology should be considered because of wide-row sowing, which leads to promoting weed growth. Besides, to prove fertilizer influents (as its amount per plant) on root system distribution (root design in heavy clay soil), fundamental studies are still needed for further progression in research.

The current results of this Ph.D. study can provide fundamental and practical support for the development of agricultural machinery, specific and conventional tools, especially for DPFA, as well as in selecting optimum material properties and improving safety factors. Moreover, this unique practical knowledge, which was obtained in terms of actual soil resistance and draft forces, will be beneficial for further research on the development of the DPFT in the Far East of Russia.

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APPENDIX 1

Table 1. Primary agricultural machinery and equipment used in PK agricultural enterprises

Designation	2016	2017	2018*	2019*
Total number of tractors	1,680	1,678	1,692	1,740
Total number of agricultural machinery and equipment	3,802	3,800	3,815	3,820
Plows	613	613	616	618
Seeders	424	424	429	431
Grass-mowing machines	170	170	172	172
Cultivators	492	492	494	494
Harrows	1,558	1,557	1,560	1,563
Tractor-trailers	446	446	446	446
Baling machines	99	98	98	96
Total number of combine harvesters	544	540	536	545
Crop harvesters	486	484	483	487
Forage harvesters	44	42	40	41
Potato harvesters	13	12	11	14
Maize (corn) harvesters	1	2	2	3

* data was collected by own observation

Source: Primstat, 2020; Department of Agriculture and Food of Primorye Territory, 2018

Table 2. Tractors on the private market in PK on May 30, 2020

Origin and Manufacturer	Total	≤10 kW	10–25 kW	25–40 kW	40–60 kW	≥60 kW
Japan	332	37	230	23	14	10
Yanmar	87	13	52	5	5	1
Iseki	80	5	52	10	3	4
Kubota	74	9	51	3	1	–
Mitsubishi	47	6	35	3	3	–
Hinomoto	11	1	10	–	–	–
Shibaura	24	1	21	1	–	–
Others[1]	9	2	9	3	4	5
China (Willig, Xingtai, Jinma)	9	–	3	1	–	2
Russia and CIS countries (Republic of Belarus, Ukraine)[2]	102	–	6	7	38	51
Europe, America [3]	15	–	–	1	1	13
Total number	458	37	239	29	33	49

[1]Hitachi, Honda, Komatsu

[2]Rostselmash, LTP (Lipetsk Tractor Plant), VTP (Volgograd Tractor Plant), MTZ (Minsk Tractor Works), YuMZ (Yuzhmash)

[3]Fendt, Massey Ferguson, Mercedes-Benz, Merlo, New Holland

Source: Drom.ru, 2020.

APPENDIX 2

Table 1. Material properties of the chisel plow model

Chisel plow part	Shank	Knife
Properties, Unit	Steel	Steel
Density (kg/m3)	7,850	7,820
Young's modulus (Pa)	2.12×10^{11}	2.11×10^{11}
Yield strength (Pa)	3.45×10^{8}	7.85×10^{8}
Tangent modulus (Pa)	7.94×10^{10}	7.94×10^{10}
Tensile yield stress (MPa)	470	735
Ultimate strength (MPa)	660	981
Poisson's ratio	0.31	0.29
Mass (kg)	10.75	1.29

Source: Sandakov et al. (2019)

Table 2. Mesh characteristics of DPFA in FEM simulation

Base Mesh (Solids): 116,134 nodes, 66,221 elements
Average Element Size (% of the model size):
Scale Mesh Size per part: 10
Max. Adjacent Mesh Size Ratio: 1.5
Max. Aspect Ratio: 10
Max. Turn Angle on Curves (Deg.): 60
Min. Element Size (% of average size): 20
Element order: Parabolic
Number of Tetrahedra: 66,386 (100% of elements (100% of volume)):
Face Angle: min – 0.652, max – 177
Dihedral Angle: min – 0.724, max – 178
Worst Shape Ratio: 202 on element 11,976
Worst Aspect Ratio: 25.7 on 8,107, shortest edge: 1.44×10^{-4}, longest: 0.048
Lowest Collapse Ratio: 7.99×10^{-3} on element 11,976
Worst Jacobian Ratio: 1 on element 1

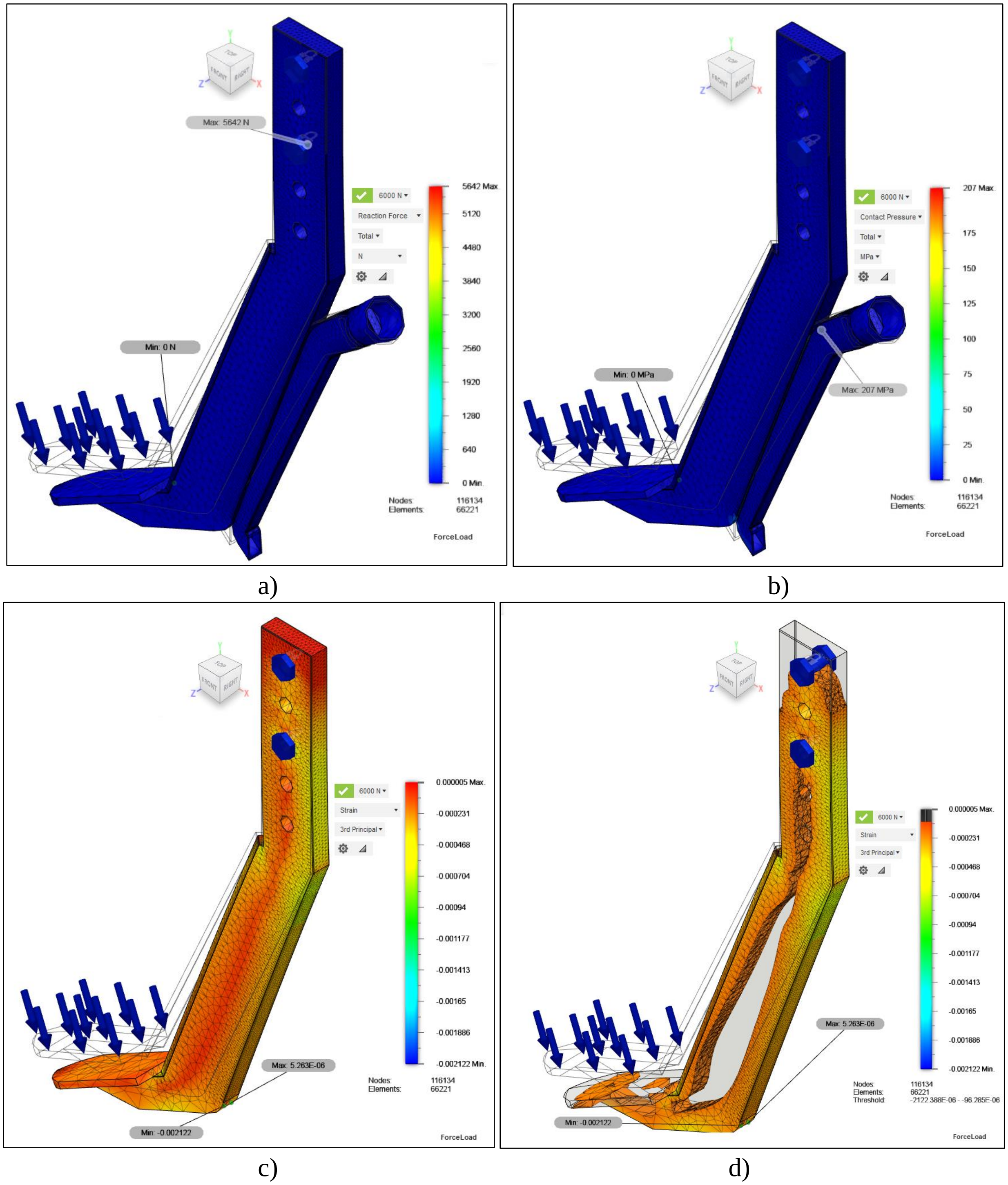
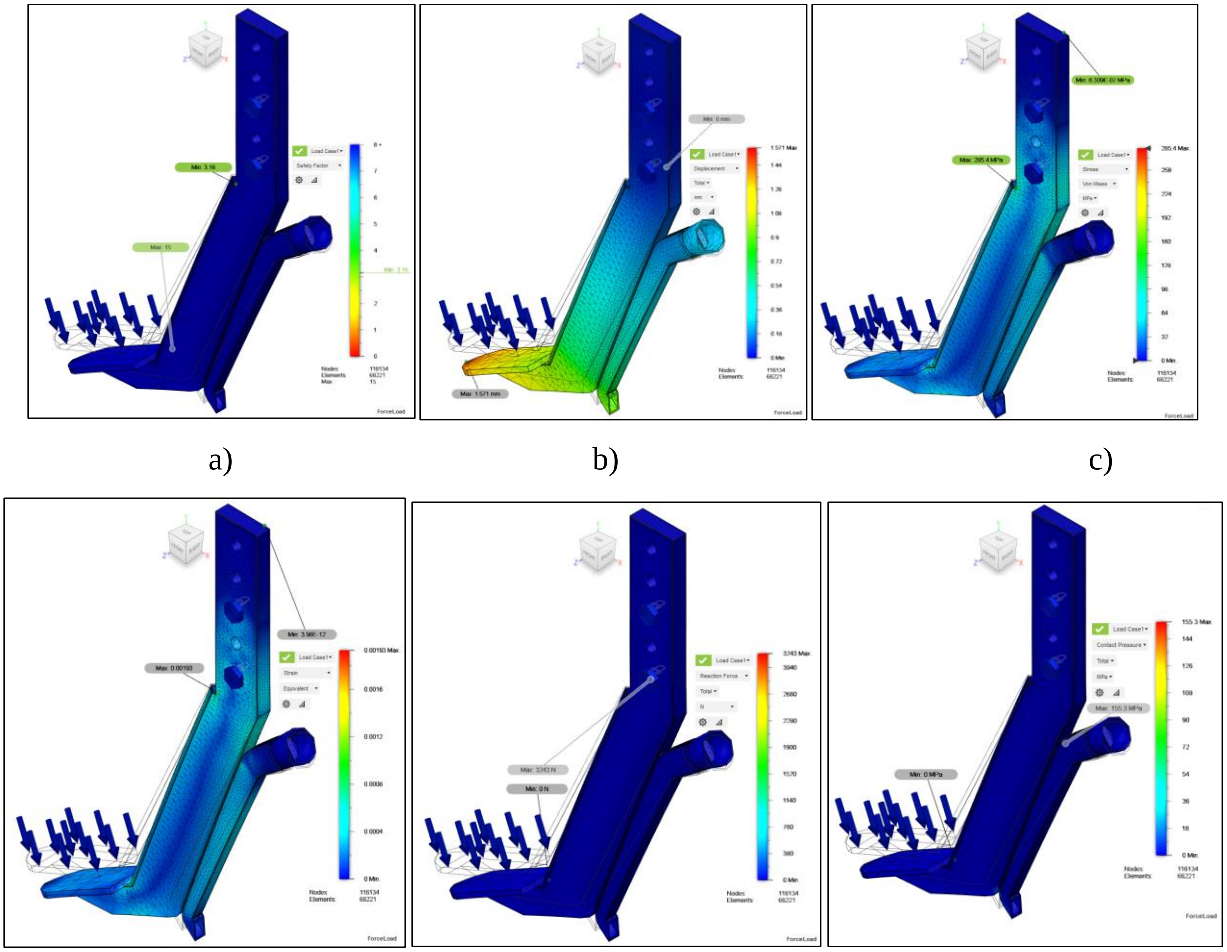


Figure 1. Results of the static analysis of the DPFA

a) – Reaction force; b) – Contact pressure; c), d) – 3rd Strain principals



a) b) c)

d) e) f)

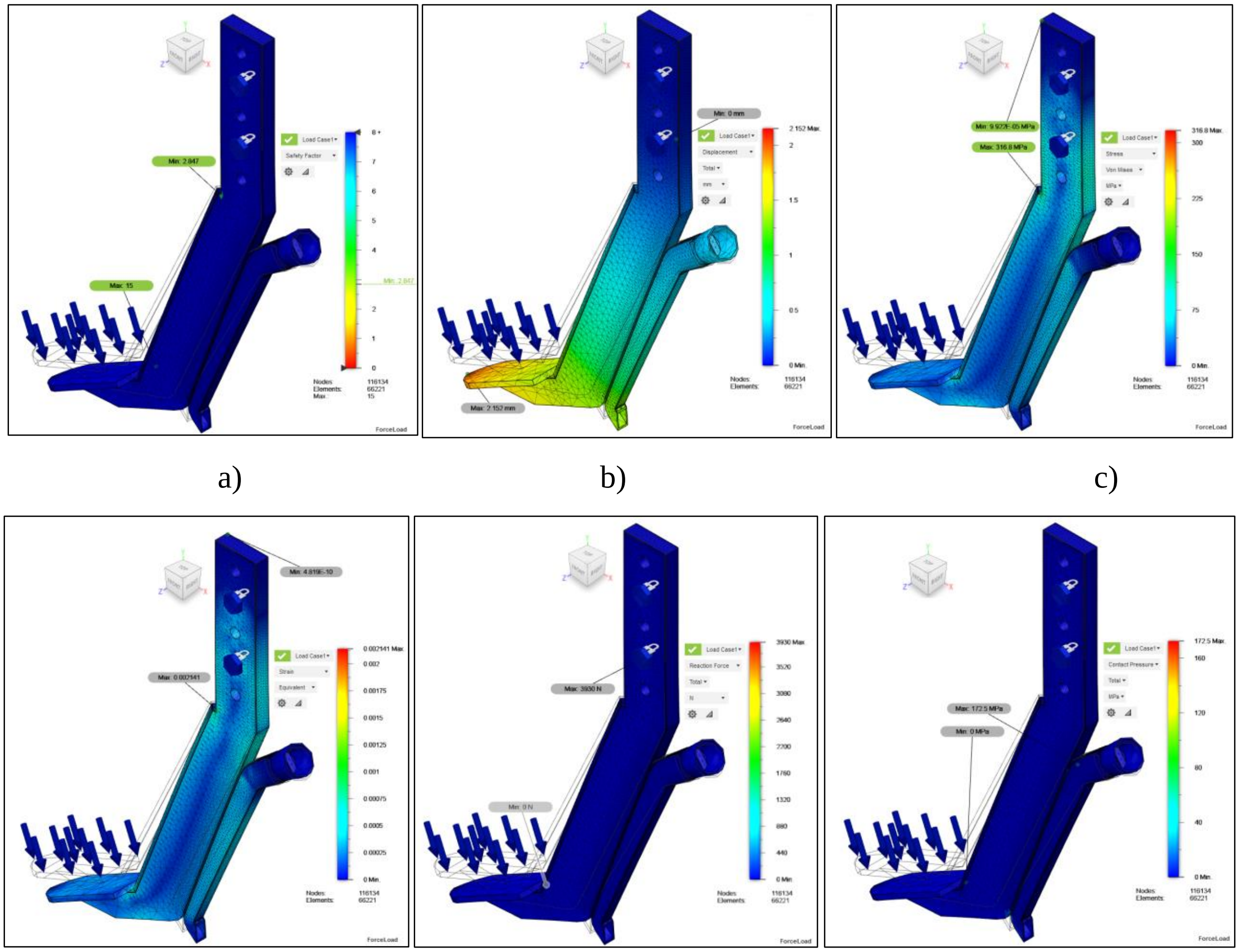
Figure 2. Results of the static analysis of the DPFA (0.15 m by 4500 N)

a) – Safety factor; b) – Displacement; c) – Stress; d) – Strain Equivalent

e) – Reaction force; f) – Contact pressure

Table 3. Result summary of 0.15 m by 4,500 N loaded force

Category	Minimum	Maximum
Safety Factor (Per Body)	3.16	15
Stress Von Mises (MPa)	6.309×10^{-7}	285.4
Displacement total (mm)	0	1.571
Reaction Force total (N)	0	3243
Strain Equivalent (mm/mm)	3.96×10^{-12}	1.93×10^{-3}
Contact Pressure total (MPa)	0	153.3



a) b) c) d) e) f)

Figure 3. Results of the static analysis of the DPFA (0.20 m by 5000 N)

a) – Safety factor; b) – Displacement; c) – Stress; d) – Strain Equivalent

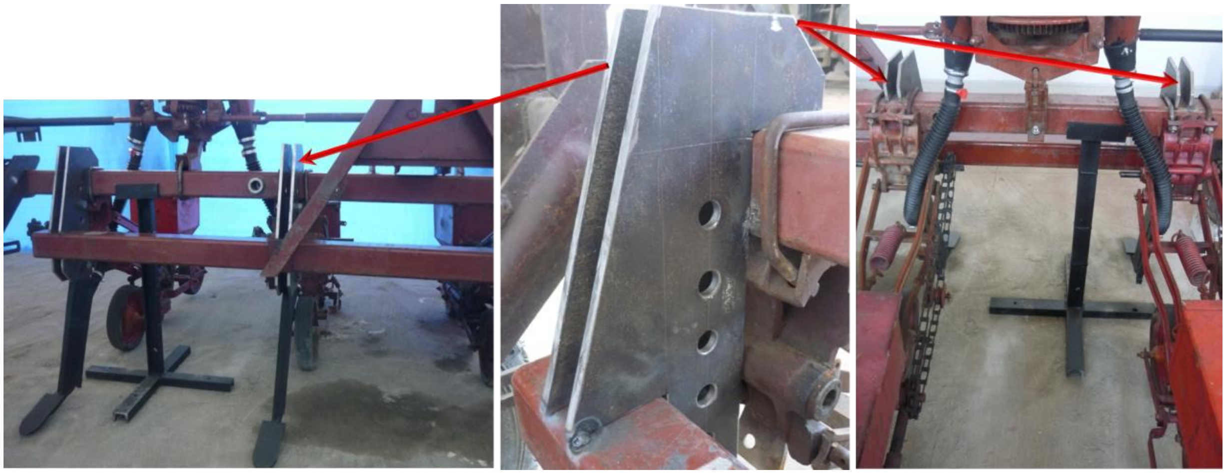
e) – Reaction force; f) – Contact pressure

Table 4. Result summary of 0.20 m by 5,000 N loaded force

Category	Minimum	Maximum
Safety Factor (Per Body)	2.84	15
Stress Von Mises (MPa)	9.922×10^{-5}	316.8
Displacement total (mm)	0	2.152
Reaction Force total (N)	0	3930
Strain Equivalent (mm/mm)	4.819×10^{-10}	2.14×10^{-3}
Contact Pressure total (MPa)	0	172.5

Table 5. Full result summary of 0.25 m by 6000 N loaded force

Category	Minimum	Maximum
Safety Factor (Per Body)	2.374	15
Stress Von Mises (MPa)	1.24×10^{-3}	379.9
1^{st} Principal	-98.81	488.7
3^{rd} Principal	-382.3	141.1
Normal XX	-177.7	278
Normal YY	-323.1	384.1
Normal ZZ	-115.3	141.4
Shear XY	-121.8	157.2
Shear YZ	-66.26	66.09
Shear ZX	-104.7	104.2
Displacement total (mm)	0	3.121
X	-7.205×10^{-3}	2.216
Y	-2.198	0.5473
Z	-4.175×10^{-3}	3.852×10^{-3}
Reaction Force total (N)	0	5642
X	-4258	1688
Y	-4027	4939
Z	-217.9	196.6
Strain Equivalent (mm/mm)	9.958×10^{-9}	2.568×10^{-3}
1^{st} Principal	-2.863×10^{-7}	2.872×10^{-3}
3^{rd} Principal	-2.122×10^{-3}	5.263×10^{-6}
Normal XX	-6.224×10^{-4}	1.05×10^{-3}
Normal YY	-1.094×10^{-3}	1.607×10^{-3}
Normal ZZ	-6.352×10^{-4}	2.532×10^{-04}
Shear XY	-1.565×10^{-3}	2.021×10^{-3}
Shear YZ	-8.514×10^{-4}	8.493×10^{-4}
Shear ZX	-1.346×10^{-3}	1.339×10^{-3}
Contact Pressure total (MPa)	0	207
X	-80.16	134.1
Y	-145.9	86.01
Z	-59.98	59.65

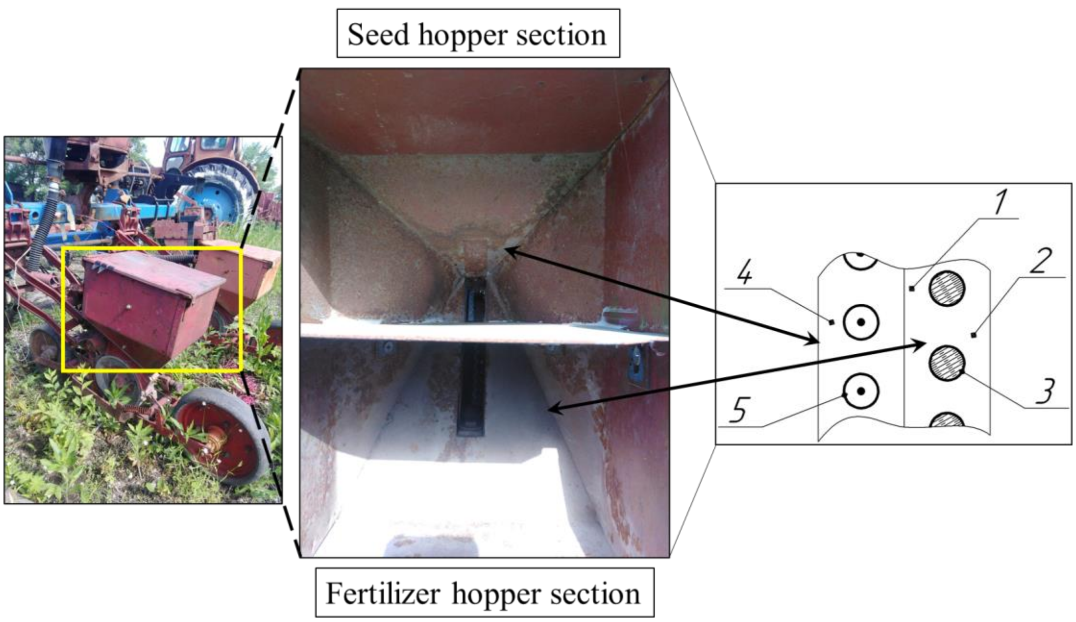


a) b) * c)

Figure 4. Fixed connecting plates to the frame construction

a) – Front view; b) – Side view; c) – Back view

* The plate thickness is 8 mm.



a) b) c)

Figure 5. The adopted seed hopper for fertilizers

4) – overview of the seed hopper; b) – Inside view of adopted seed hopper; c) – Arrangement of seeds and fertilizers in the feeding mechanism per one cell

(1 – Distribution disk of the feeding mechanism; 2 – A row of fertilizers; 3 – Fertilizer; 4 – A row of seeds; 5 – Soybean seed)

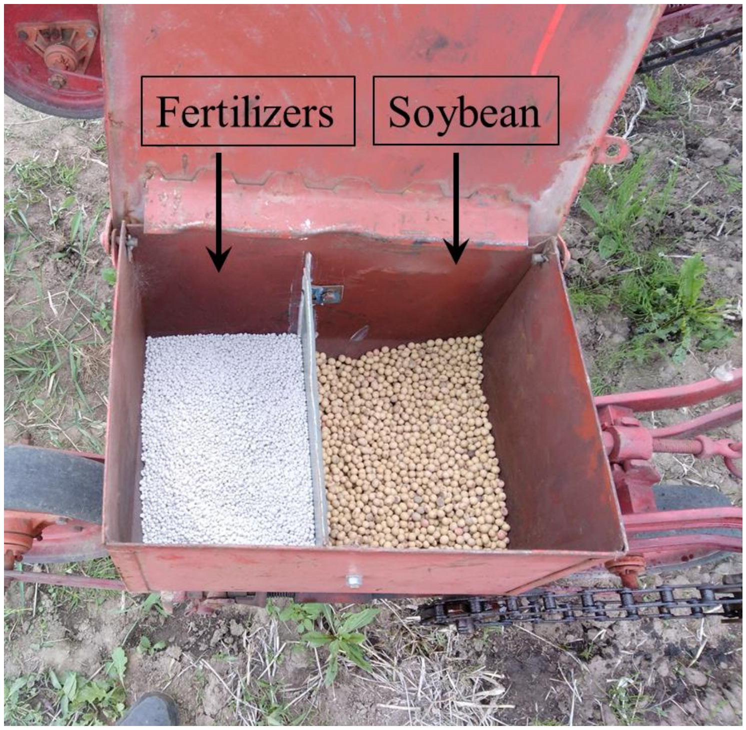


Figure 6. Fertilizers and Soybean are placed in adopted hopper

Fertilizers – NPK (10:26:26); Soybean variety – Primorskaya 86

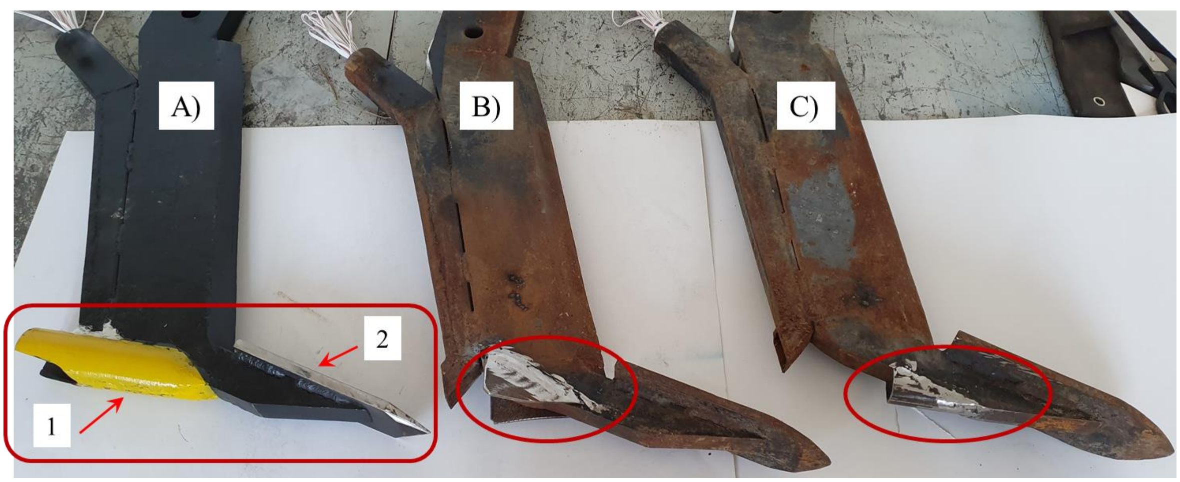


Figure 7. The improved DPFAs

a) – Cylinder-shaped type; B) – Hoes (Weed knives type); C) – Plate type

– The improved area.

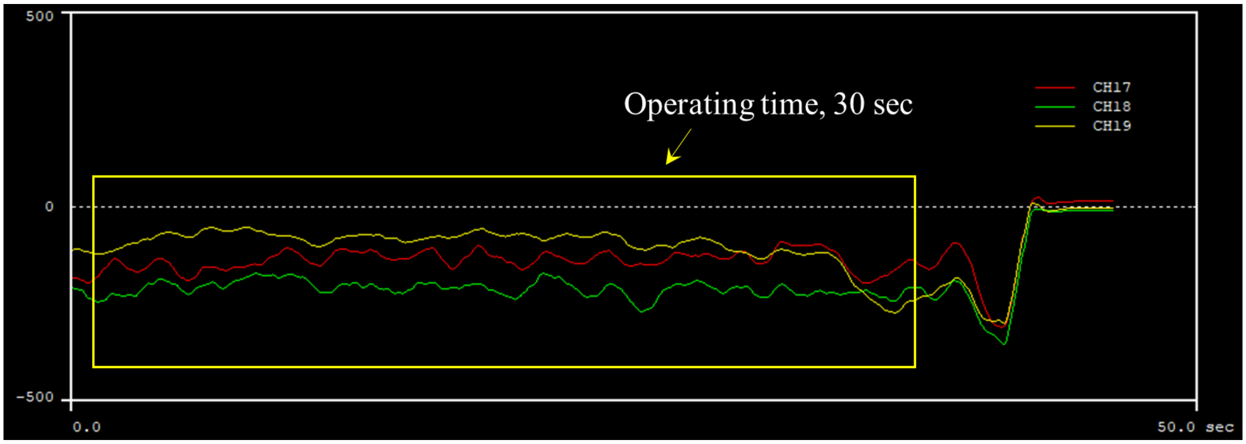


Figure 8. The comparison of improved DPFAs at 0.20 m depth

CH17 – Plate type; CH18 – Hoes (Weed knives type); CH19 – Cylinder-shaped type

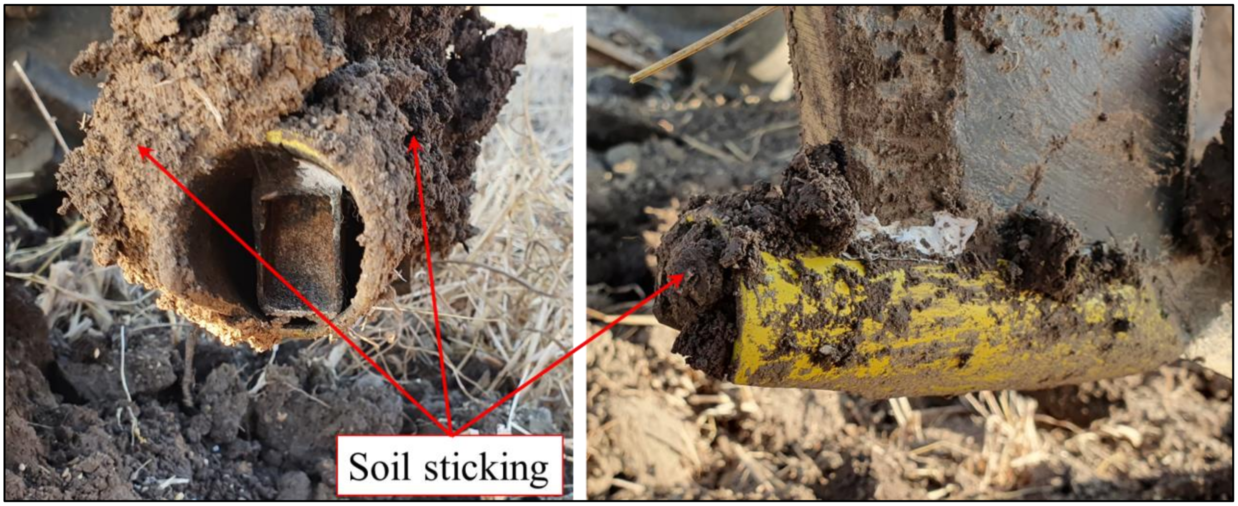


Figure 9. Surrounded area of the fertilizer canal maker by clay soil

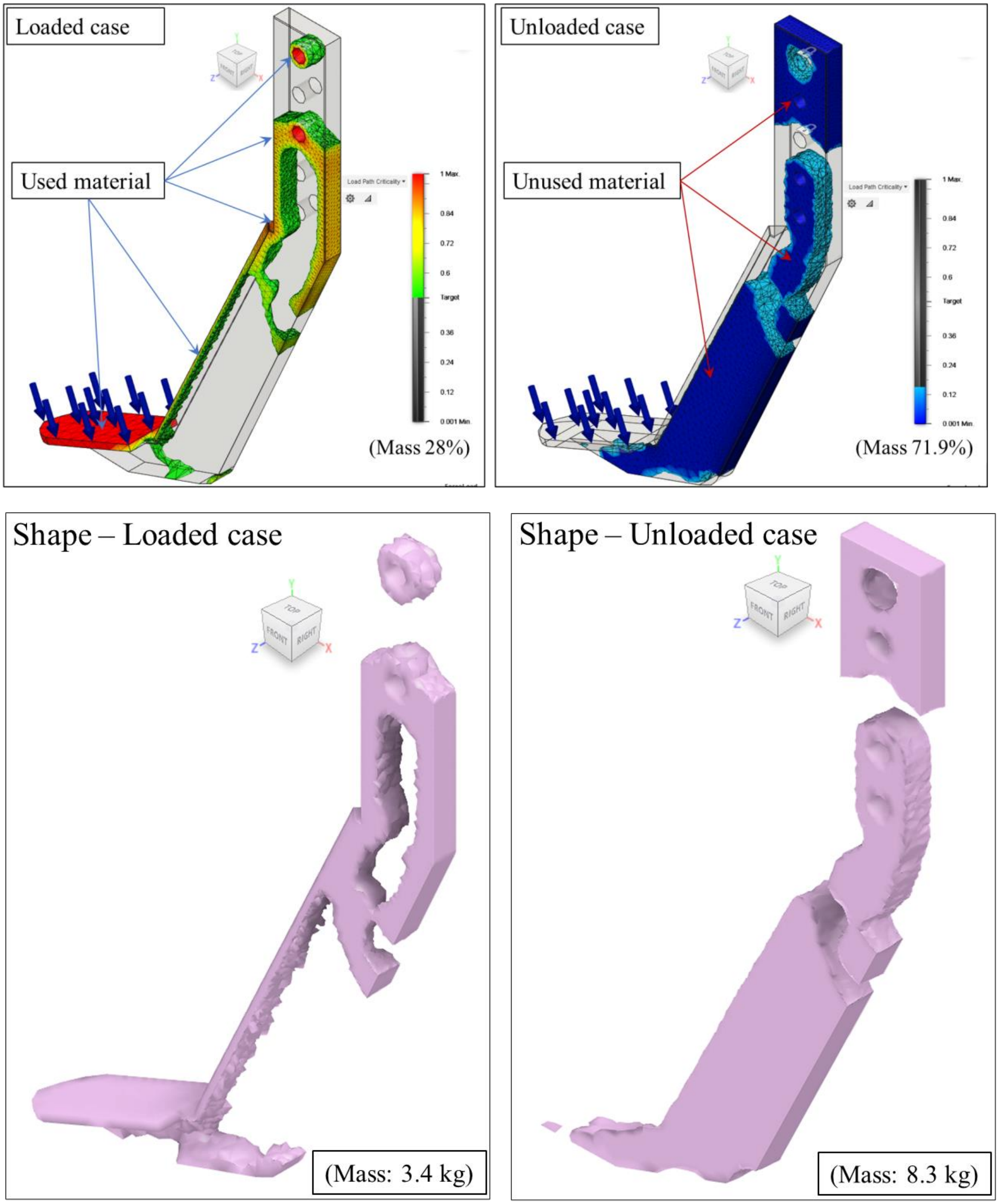


Figure 10. A draft shape results (Total mass analysis)

APPENDIX 3

Table 1. Control plot (no DPFT)

No. Plant	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Stem height, cm	70	70	70	71	71	70	75	72	70	70
No. of Beans	44	50	33	39	44	34	58	71	50	52
No. of Seeds	73	97	78	83	78	58	104	137	102	114
1 seed in a bean	16	11	5	9	10	11	16	20	14	10
2 seeds in a bean	16	16	5	17	16	12	21	34	22	18
3 seeds in a bean	7	18	21	12	12	5	14	15	8	20
4 seeds in a bean	1	0	0	1	0	2	1	1	5	2
Not developed beans	4	5	2	0	6	4	5	1	1	2
AV. No. Seeds per plant						92				
AV. No. Beans per plant						47				
AV. Mass of 1000 seeds (from three repetitions), g								132.9		

Table 2. DPFT – 0.15 m

No. Plant	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Stem height, cm	73	75	75	75	80	75	80	74	75	70
No. of Beans	37	63	59	54	43	48	44	48	43	50
No. of Seeds	86	151	110	92	84	93	92	94	86	95
1 seed in a bean	6	8	11	15	10	12	5	8	12	13
2 seeds in a bean	11	15	23	16	16	20	18	16	14	19
3 seeds in a bean	18	27	15	11	10	11	13	18	10	12
4 seeds in a bean	1	8	2	3	3	2	3	0	4	2
Not developed beans	1	5	8	9	5	3	7	6	3	4
AV. No. Seeds per plant						98				
AV. No. Beans per plant						49				
AV. Mass of 1000 seeds (from three repetitions), g								139.25		

Table 3. DPFT – 0.20 m

No. Plant	1	2	3	4	5	6	7	8	9	10
Stem height, cm	80	80	75	75	78	80	75	80	75	75
No. of Beans	69	49	51	83	66	59	56	56	51	58
No. of Seeds	147	123	122	156	147	142	126	133	127	134
1 seed in a bean	10	3	8	9	8	8	7	6	6	9
2 seeds in a bean	25	12	10	29	28	21	16	18	15	15
3 seeds in a bean	25	28	26	23	21	20	25	21	25	21
4 seeds in a bean	3	3	4	5	5	8	3	7	4	8
Not developed beans	2	3	3	5	4	2	5	4	4	5
AV. No. Seeds per plant					136					
AV. No. Beans per plant					60					
AV. Mass of 1000 seeds (from three repetitions), g							143.83			

Table 4. DPFT – 0.25 m

No. Plant	1	2	3	4	5	6	7	8	9	10
Stem height, cm	73	75	70	75	80	75	74	75	75	80
No. of Beans	64	49	55	42	42	72	47	74	44	47
No. of Seeds	128	86	100	77	79	133	82	153	77	88
1 seed in a bean	17	13	12	6	9	27	11	10	14	13
2 seeds in a bean	9	20	15	17	12	18	13	30	13	15
3 seeds in a bean	27	11	18	11	14	18	11	25	11	15
4 seeds in a bean	3	0	1	1	1	4	3	2	1	0
Not developed beans	8	5	9	7	6	5	9	7	5	4
AV. No. Seeds per plant					100					
AV. No. Beans per plant					54					
AV. Mass of 1000 seeds (from three repetitions), g							143.75			

Table 5. Additional data on conventional planting (Row spacing 0.15m)

No. Plant	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Stem height, cm	84	76	84	80	79	78	81	86	83	82
No. of Beans	16	26	22	27	21	23	23	24	20	23
No. of Seeds	38	48	47	52	40	49	44	43	40	42
1 seed in a bean	2	5	2	6	5	3	8	6	5	9
2 seeds in a bean	7	14	9	11	10	9	9	14	10	9
3 seeds in a bean	6	5	9	8	5	8	6	3	5	5
4 seeds in a bean	1	0	0	0	0	1	0	0	0	0
Not developed beans	0	2	2	2	1	2	0	1	0	0
AV. No. Seeds per plant						44				
AV. No. Beans per plant						22				
AV. Mass of 1000 seeds (from three repetitions), g								–		

Data on used seed and fertilizer rates

Base (Surface) Fertilizer Application (Estimated Value)

Since the volume of the seed hopper was divided into two sections for a fertilize hopper (to apply base fertilizers), therefore the fertilizer hopper will be approximately the same as the seed hopper volume. Moreover, it can be accepted that the bulk weight (volume) of soybean seeds is approximately the same as the weight of the fertilizer (which is placed in 1 cell, (Fig. 4, App. 2)). Thus, the base fertilizer rate can be count as the seeding rates as follows (Fig. 1):

Calculation of a seed spacing for 0.05 m:

100 m / 0.05 m = 2,000 seeds (pcs) in a row

143 × 2,000 = 286,000 pcs/ha

With a weight of 1,000 seeds = 160 g, the weight of 1 grain = 0.16 g (0.00016 kg/ha)

Seed weight per hectare: M_S = 286,000 × 0.00016 ≈ 46 kg/ha

It follows that the mass of the base fertilizer (M_F) is M_F ≈ 46 kg/ha.

Calculation of a seed spacing for 0.10 m:

100 m / 0.10 m = 1,000 seeds (pcs) in a row

143 × 2,000 = 143,000 pcs/ha

Seed weight per hectare: M_S = 143,000× 0.00016 ≈ 23 kg/ha (M_F ≈ 23 kg/ha).

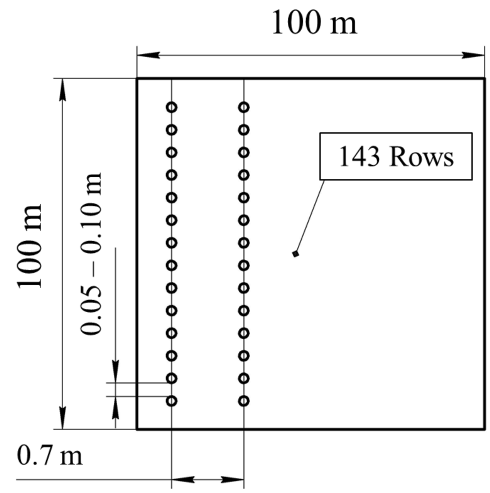


Figure 1. The arrangement of soybean seeds per 1 ha

0.05 – 0.10 m – Distance between soybean seeds; 0.7 m – Row spacing

Deep fertilizer application

According to the experiment scheme (Fig. 10, Ch. 3), the first plot (control) was sown without deep fertilizer application, and for other 3 plots was sown of 6.7 kg fertilizers per (deep) fertilizer hopper. Thus, the deep fertilizer (D_E) rate per experimental plots can be calculated as follows:

Seed spacing (h) = 0.05 m (3 plots of 4 rows):

3 × 4 × 65 (row length) × 0.7 = 546 m^2 = 0.0546 ha

D_E by 0.05 m = (6.7 / 3) × 2 = 4.47 kg.

Seed spacing (h) = 0.1 m (3 plots of 4 rows):

3 × 4 × 65 × 0.7 = 546 m^2 = 0.0546 ha

D_E by 0.1 m = 6.7 – 4.47 = 2.235 kg.

Consequently, the deep fertilizer rate per 1 ha (D_H) can be calculated as follows:

Seed spacing h = 0.05 m:

$D_{H0.05}$ = 4.47 / 0.0546 = 81.87 kg/ha.

Seed spacing h = 0.1 m:

$D_{H0.1}$ = 2.235 ÷ 0.0546 = 40.93 kg/ha