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Economic and Environmental Effects of Innovative Potato Cultivation with the Use of Beneficial Microorganisms in Poland

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Abstract
Agricultural production is the main area of human activity that affects both food security and well-being, as well as the environment, in which people live. The modern economy tries to combine economic and environmental goals, because uncontrolled intensive production growth can lead to irreversible changes in the environment. This paper addresses the issue of evaluating one of the methods in search of the golden mean of sustainable agricultural production, on the example of the potato-microbiome interaction leading to the development of an innovative strategy of potato breeding and production. The aim was to apprise the economic and environmental effects of innovative potato cultivation with the use of beneficial microorganisms in Poland based on the field data. The data for the analyses were obtained from experimental field work carried out in 2021–2022 under the PotatoMetaBiome project. The analysis of the collected data allowed us to conclude that from the economic point of view, the most profitable was the strategy that included the use of practices based on synthetic means of production (with mineral fertilizers and chemical protection). On the other hand, the use of innovative preparations with beneficial microorganisms slightly increased the profitability in relation to the strategy without means of production and with the use of synthetic means of production. At the same time, it had the least negative impact on the environment than other agricultural practices. The obtained results indicate that the use of beneficial microorganisms may be a viable alternative agricultural strategy in potato production. It allows farmers to obtain satisfactory economic results while maintaining the environmental regime. Their use, however, requires further research in terms of the impact on the economics and organisation of agricultural production.

1. INTRODUCTION

The current model of economic growth, which assumes striving to improve the living standards of the society, causes an increasingly rapid degradation of the natural environment and contributes to the loss of biodiversity through greater consumption of resources and higher emissions [Otero et al. 2020; Ekins, Zenghelis 2021]. Agricultural production has a significant share in the intensive exploitation of natural resources or the use of non-environmentally friendly production technologies. Currently, many studies address the issue of assessing the impact of agricultural production on the environment. As the results show, agricultural production that is too intensive causes changes that are usually unfavourable [Lankoski, Ollikainen 2003; Hediger, Lehmann 2007; Gołębiewska, Pajewski 2016], although Garcia [2020] points out that the intensification of agriculture is necessary to meet the growing global demand for food, which, as indicated by Sundström et al. [2014] is one of the most pressing issues for humanity. This is confirmed by the analyses of van Dijk et al. [2021] that indicate that consumption trends and global population growth will result in the world needing 60% more food by 2050 than is currently available. This will put additional pressure on natural resources involved in food production [Ritchie et al. 2022].

To increase agricultural production and maintain soil fertility, the use of mineral fertilizers is essential [Bisht, Chauhan 2020]. However, improper and excessive use of mineral fertilizers or plant protection products poses a threat to the environment [Fasusi, et al. 2021] and has a detrimental effect on the nutritional value of agricultural products and the health of farmers and consumers [Alori, Babalola 2018]. On the other hand, restrictions on the use of means of production result in lower yields [Popp et al. 2013; Kirchmann 2019; Bogusz et al. 2021; Kalogiannidis et al. 2022; Gopinath et al. 2023]. Therefore, it is important to take action to look for solutions that will reduce the negative impact on the environment while ensuring optimal income for farmers.

Therefore, in order to maintain appropriate economic results for agricultural farms, while protecting the

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environmental resources used, it is necessary to introduce innovative solutions [Yu, Wu 2018; Islam 2018]. Innovative practices in agricultural production can be used on the farm as an approach to food production in a more natural way [Maciejczak, Filipiak 2020; Viana et al. 2022]. This is a very important issue because, as Struik, Kuyper [2017] stated, society needs agriculture that is resilient to future changes and that is able to cope with the diversity of trade-offs between different stakeholders. Therefore, it is important to ensure sustainable development, which is perceived as a dynamic process based on values and common knowledge.

The direct dependence of plant agricultural production on environmental conditions means that the cultivation of field crops is closely related to many factors influencing the growth and development of plants. Potatoes were selected for the study as one of the most frequently planted vegetables [Zhang et al. 2017]. In 2016, according to Hussain [2016], potatoes were grown in over 100 countries. At the same time, the number of potato-producing countries is steadily increasing. According to the estimates by Calışkan et al. [2023], in the following years it was already in almost 150 countries. Potatoes rank fourth in terms of human consumption in the world, after maize, wheat and rice [FAOSTAT 2020]. As pointed out by Calışkan et al. [2023], sustainable potato production is critical to future food security and social sustainability.

The aim of the study is to analyse the profitability of potato production in a system in which the use of mineral fertilizers and chemical plant protection products will be replaced by the use of selected potato varieties that effectively cooperate with selected beneficial microorganisms, which were the basis of innovative preparations for agricultural production as microbial inoculants. The assessment was made by comparing the results of the potato-microbiome interaction and the results of production using traditional methods. The obtained results made it possible to determine the differentiation of the impact of selected potato cultivation methods on economic and environmental effects.

MATERIALS AND METHODS

The works have been done under the international multidisciplinary project PotatoMetaBiome. The detailed description of research executed in this project were presented i.a. by Treder at al. [2021]. Experimental field work was planned and carried out in Poland in the growing seasons of 2021 and 2022 at the Institute of Plant Breeding and Acclimatization, branch in Bonin. During the experiments, economic data related to the cultivation of potatoes in field conditions using production strategies without and using interactions with beneficial microorganisms were collected.

In order to compare the environmental impact of potato cultivation, the Eco-indicator 99 method was used, which is one of several methods used in Life Cycle Assessment (LCA) to assess and determine the environmental mechanism. Eco-indicator 99 reflects the current state of knowledge in the field of LCA methodology and applications [Manual for… 2020]. The supply of raw materials (planting material, fertilizers and plant protection products) and cultivation processes (soil preparation, planting, sowing fertilizers, plant protection treatments, weed control, harvesting) were taken into account. Life-cycle analysis was performed using SimaPro software. Agri-foodprint 5 and Ecoivent 3 databases were used. Agri-footprint is a high-quality and comprehensive Life Cycle Inventory (LCI) database focused on agriculture and the food sector. It includes data on agricultural products: feed, food and biomass and is used by LCA practitioners. It contains a methodologically consistent set of data for a large number of crops, plant products, animal systems and products of animal origin [Durlinger et al. 2014]. It is a global library of human activities that includes thousands of processes that deliver goods and services in all sectors [The Ecoinvent… 2022].

As part of the economic assessment, a cost-effectiveness analysis was carried out. The approach is similar to the one proposed by Dickinson et al. [2015]. The profitability of production was determined using the ratio calculated as sales revenue to production costs [Ziętara, Olko-Bagieńska 1986]. As pointed out by Zhichkin et al. [2019], the indicator calculated in this way can be used both as a whole for the enterprise and for its individual units or types of products.

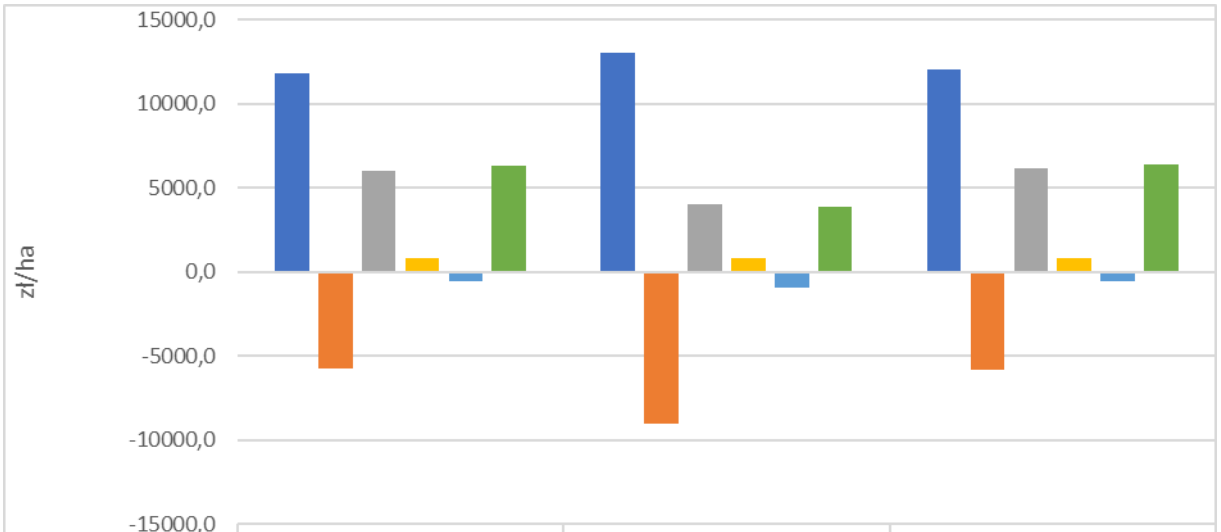
Three strategies differing in fertilization and chemical protection of potatoes were analysed in the study, namely:

- I – without mineral fertilization and without chemical protection
- II – mineral fertilization with chemical protection
- III – without mineral fertilization and chemical protection with the use of beneficial microorganisms

The calculations assumed, in the first version, the same selling prices of PLN 0.50 per 1 kg, while in the second version, 30% higher prices were taken into account for variants without fertilization and chemical protection, as organic variants [Łuczka 2020]. Only healthy potatoes were used in the analyses, which constituted the commodity plan, converted to 1 ha in individual experiments. In order to eliminate the influence of natural conditions, the obtained results were averaged for the 2021 and 2022 seasons.

RESULTS AND DISCUSSION

The conducted analyses allowed to determine the effect of beneficial microorganisms on the economics of potato production. Figure 1 shows the obtained results as average values for the analysed seasons at the same selling price. It was found that the highest sales revenues were obtained for the strategy in which fertilization and chemical protection were used. However, in this variant, the costs incurred for the production of potatoes were almost 49% higher than for the variants without fertilization. Hence, the final result (income) for this type of variant was the lowest. It should also be pointed out that when comparing the strategy



	I	II	III
Total sale	11802,5	13040,0	12046,3
Total direct costs	-5747,0	-9044,5	-5854,4
Gross margin	6055,5	3995,5	6191,9
Subsidies	828,0	828,0	828,0
Indirect costs	-574,7	-904,5	-585,4
Profit	6308,8	3919,1	6434,5

* Variant: I – without fertilization and without chemical protection; II - fertilization with chemical protection; III - without fertilization and chemical protection with the use of beneficial microorganisms.

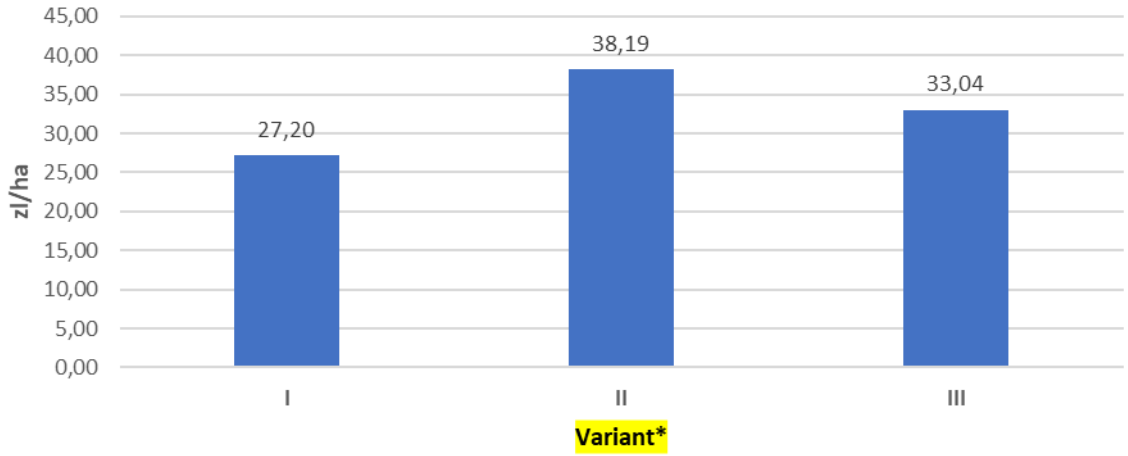
Figure 1. Analysis of the profitability and costs of the adopted potato cultivation strategies in the 2021–2022 seasons (average healthy yield) (zl/ha)
Source: own study

without fertilization and chemical protection with the use of beneficial microorganisms, more favourable economic results were obtained in the last case. These differences were not significant, amounting to approx. 2%. One needs to remember that the results were analysed only for a two-year period, which affected the results. Therefore, it may be important to conduct further observations that will, on the one hand, eliminate the impact of weather factors, which, as reported by Gruczek [2004] and Trawczyński [2020], are the superior group of factors determining the yields obtained, and, on the other hand, changes in the soil environment (e.g. crop rotation).

The costs of potato production with the use of beneficial microorganisms were only slightly higher than the variant without fertilization and chemical protection, while the income was slightly higher. This proves the positive role of microbiological inoculants in achieving higher economic results while protecting the environment. The positive role of microorganisms has been noticed in many studies. Vishnu [2022] states that they help plants access nutrients in the soil. The use of such preparations in plant cultivation, as indicated by Ertani et al. [2014], can bring many benefits, such as an increase in the activity of soil microflora, better development of the root system and intensification of the production of growth regulators both in the soil and in plants. The advantage of using biological microorganisms is also the fact that the obtained crops can be treated as ecological, which additionally enables obtaining a higher selling price. In our research, taking into account only a 30% increase in the selling price, the results would be higher by approximately 55%.

Studies indicate that the use of microbial inoculants increases the yield of potatoes compared to a strategy that does not use such agents. Such results were obtained in the study by Song et al. [2021], suggesting that soil microorganisms improve potato yields, which is a solid basis for the use of biological control in crop production. In our research, the yields obtained were significantly higher in strategy III only in the first year of research. In the next one, they were at a similar level as in strategy I – without fertilization and chemical protection. This could be due to the use of a different variety in the second year of research. This is indicated by Ertani et al. [2018], stating that the effect of biostimulators may vary depending on the plant species or even the variety.

Conclusions indicating the importance of biostimulators were also obtained by Buddolla [2019], who showed that inoculants are cheap, sustainable and safer for the environment than chemical fertilizers. The use of a microbiological product in potato cultivation was also



* Variant: I – without fertilization and without chemical protection; II - fertilization with chemical protection; III - without fertilization and chemical protection with the use of beneficial microorganisms.

Figure 2. Cost of production of 1 dt of potatoes according to the average yield of in applied strategy (zl)
Source: own study

positively assessed by Wang et al. [2019], stating that it contributed to an increase in yield and inhibition of fungal diseases (potato scab). Research by Chen et al. [2022] also highlight the potential impact of biological and abiotic factors on crop growth, with important implications for preserving microbial diversity underground and maintaining crop productivity. Positive results in the use of inoculants were also obtained by Contreras-Liza et al. [2022]. Li et al. [2022] conclude that soil microorganisms can be used alone or in combination with reduced amounts of agrochemicals to promote sustainable agriculture. Hence, it can be concluded that beneficial microorganisms can be, as reported by Solanki et al. [2023], helpful in reducing the amount of fertilizers used.

In our research, we also found that, in addition to environmental factors, the cost factor is also important. The use of chemical fertilizers and plant protection products significantly increased the costs of potato cultivation, contributing, despite higher yields, to lower income. Based on the comparison, it was found that the production costs of 1 dt of potatoes fluctuated depending on the adopted strategy in the period 2021–2022 (Fig. 2). The lowest costs were characterised by strategy I (without fertilization and protection measures) and the highest by strategy II with high production intensity.

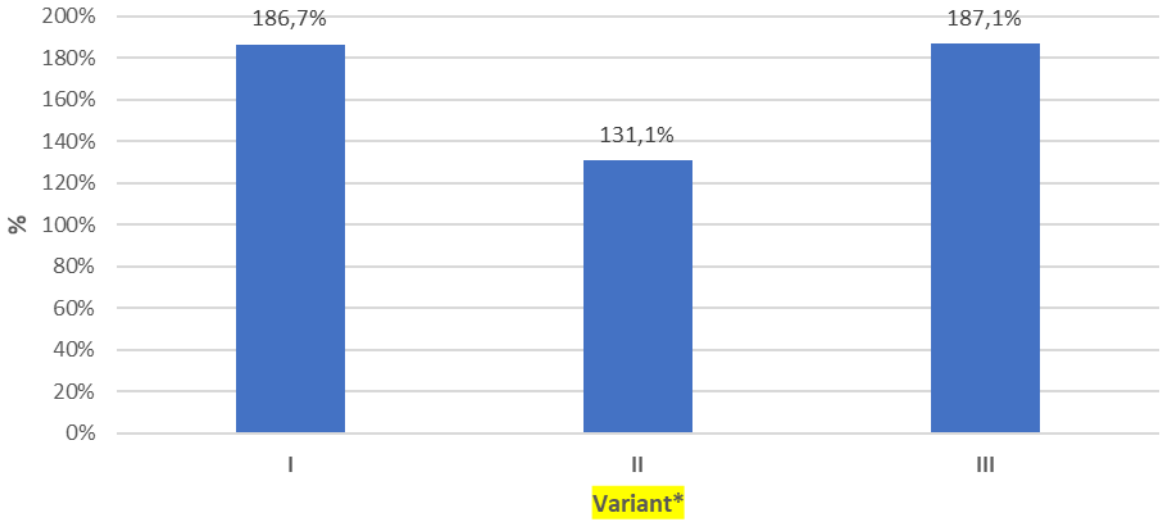
High production costs were of great importance in determining the profitability of production. The comparative analysis of the profitability index shows that in the case of the version of the microbial inoculant, the production profitability was the highest, and the difference in relation to the profitability of production without agrotechnical measures was about 2 percentage points. In contrast, it was significantly higher than using strategy II, which used chemicals (Fig. 3).

Results showing an increase in the productivity of potato seed tubers with the use of microbial inoculants were also obtained by Torres-Vite, Con-treras-Liza [2019] or Wang et al. [2021]. Hijri [2016] found that inoculation was profitable with an increase in yields of 0.67 tonnes/ha, indicating significant economic benefits. The assessment of benefits and costs allowed us to conclude that the most cost-effective agrotechnical strategies in the evaluated experiment should be considered the option without fertilization and without chemical protection, and the option without fertilization and chemical protection, but with the use of beneficial microorganisms. The least profitable strategy turned out to be the option using synthetic plant protection products (fertilization and chemical protection).

In addition, when assessing the impact on the environment, results were obtained at impact points, which were presented in intermediate categories of environmental damage according to Eco-indicator 99 of LCA methodology [Manual for… 2020] then grouped into three final categories, which were also applied in other research [Piotrowska et al. 2019]:

– human health (intermediate categories: carcinogenicity, inorganic respiratory hazards, organic respiratory hazards, climate change, radiation, ozone layer reduction),
– environmental quality (intermediate categories: ecotoxicity, acidification /eutrophication, land take), and
– resource consumption (intermediate categories: minerals, land take, fossil fuels).

Figure 4 shows the total impact of potato production on the environment for the adopted cultivation strategies. It was found that the use of any agricultural practices related to the use of machinery and equipment increases the environmental impact. Pawlak [2015] reached similar conclusions.



* Variant: I – without fertilization and without chemical protection; II - fertilization with chemical protection; III - without fertilization and chemical protection with the use of beneficial microorganisms.

Figure 3. Profitability indicators of potato cultivation in 2021–2022
Source: own study.

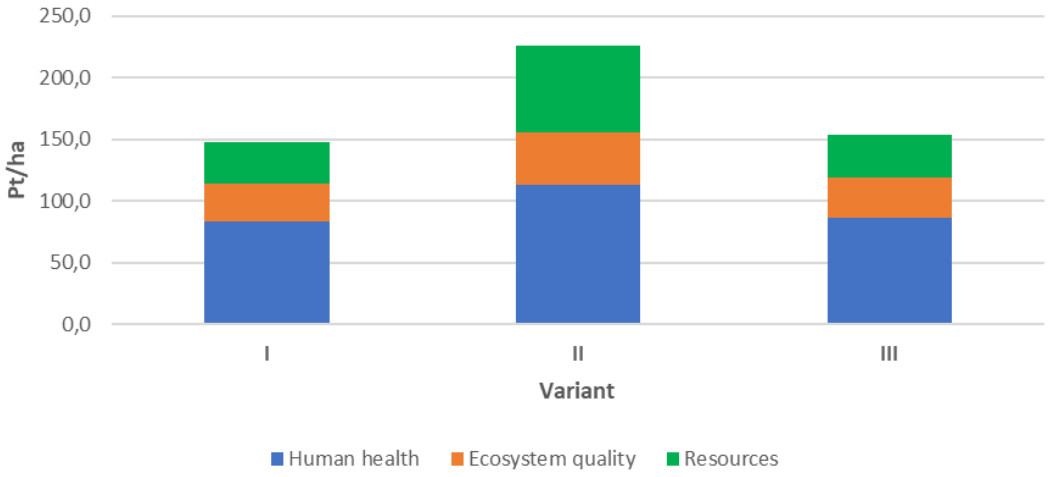


Figure 4. Total environmental impact of potato production for the adopted cultivation variants on average in 2021–2022
Source: own study

Regarding the impact of the tested agronomic strategies on the environment, it can be concluded that the smallest negative impact on the environment (148 Pt/ha) was obtained in the case of technology in which fertilization, plant protection products and preparations were not used. In the case of variants where microbial inoculants were used, the negative environmental impact expressed in Pt/ha of crops was less than 4% higher vs. the variant where fertilization and plant protection products were not used. In option II, in which both mineral fertilization and plant protection products were used, the pressure on the environment was 76 Pt/ha (approx. 51%) higher than in option I (without fertilization and plant protection products). This resulted from a greater number of agrotechnical treatments and the need to produce and transport the applied fertilizers and plant protection products.

It was found that the potato production has the greatest negative impact on the category of human health (in all variants), especially through the emission of inorganic substances that pose a threat to the respiratory system. As Alengebawy et al. [2021] state, toxicants pollution is a critical environmental concern that has posed serious threats to human health and agricultural production. In

our research, of course, the greatest threat is posed by the variant with the use of mineral fertilizers and chemical plant protection products. The smallest negative impact of potato production was obtained in the category of environmental quality, and the decisive factor in this category is the consumption of fossil fuels and land occupation, that is, the replacement of natural ecosystems with crops. Also, the highest share of fuel consumption was obtained with strategy II (with fertilization and chemical protection), and the lowest with option I.

When assessing the environmental impact, averaging the results for individual variants, it was found that the use of any agrotechnical practices related to the use of machinery and equipment increases the environmental impact. Thus, the strategy of not using any agrotechnical measures (variant I) had the lowest total environmental impact (148.33 Pt/ha). However, with regard to the strategy in which synthetic plant protection products and mineral fertilizers are used (variant II), where the environmental impact is 51% higher compared to the strategy of not using any agents, the use of microbiological substances less negatively affects the environment. This impact only increases by less than 4% compared to a no-measures strategy.

However, so far, a limited number of farmers, whom should be treated as innovators, use microorganisms in plant cultivation. On the one hand, the mineral fertilizers and chemical plant protection products used so far are a proven way to obtain high yields. On the other hand, research on the effects of biological preparations in plant production, especially based on beneficial microorganisms, is ongoing. In particular, the production and economic results of such applications are examined in an applied manner. Because these are experimental works in natural conditions, their effects often depend on weather conditions. Therefore, it requires an extension of the research period in order to obtain reliable results.

CONCLUSION

The results of the conducted research showed that the application of beneficial microorganisms in the potato production, while using also selected varieties, can be a successful alternative to the traditional agronomic strategy applying synthetic fertilizers and plant protection. Based on the executed field experiments, from the economic perspective, the most cost-effective strategy of potato production could be production using beneficial microorganisms and production without fertilization and chemical protection. The profitability ratio for these strategies was, respectively, 186% and 187.1%. It should be emphasised that these variants potato yields were not the highest. The highest yields were obtained in the strategy in which synthetic agrotechnical means were used. However, high production costs made this strategy the least profitable. The strategy of using microbial inoculants lower the environmental impact, compared to using synthetic production means. From the analysed three categories of environmental impact, the smallest negative impact in case of using microbial inoculants was obtained in the category of environmental quality.

The obtained results indicate that the use of beneficial microorganisms may be a viable alternative potato production strategy. Their use, however, requires further research in terms of the impact on the economics and organisation of agricultural production. We argue, following also Hara [2019], that research on the possibility of using biostimulators in potato cultivation should be continued in order to obtain knowledge on the method of dosing these preparations depending on many factors (e.g. cultivated variety potato). The conducted research has certain limitations resulting from the experimental nature of field research and the only two-year period of data collection, as well as only one location of research. Obtaining results under changing natural conditions in several growing seasons is therefore necessary, which is a premise for continuing the research.

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