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ORIGINAL PAPER

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ECONOMIC ASSESSMENT OF THE BIOLOGICAL AGENT USE IN ECOLOGICAL POTATO PRODUCTION – SYSTEM DYNAMICS SIMULATION

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ABSTRACT

Aim: The aim of this study is to assess the economic viability by calculating the potential profits and expenses for farmers, and to simulate the impact of the application of a microbiological agent on the potato plant in a field trial. The field experiment aimed to identify the role of the biological agent while substituting the synthetic plant fertilization and protection. **Methodology:** The system dynamics method was applied to the data provided from one planting season of field experiments conducted in the framework of the PotatoMETABiome project. From eleven tested varieties on six different scenario plots, the most economically viable variety – Pasja Pomorska – was tested. The comparative approach was applied to show the results of inoculating potato plants with biological agents and using synthetic pesticides and fertilizers. **Results:** The results show that the application of biocontrol agents increases the quality and quantity of the potato yield compared to a variant in which no synthetic agents are used. These are, however, higher while applying the latter. It can therefore be argued that the microbiological agent could support ecological potato production, yet it does not reach the economic break-even point yet. **Conclusions:** Bearing in mind the limitations resulting from the experimental nature of field research, the level of economic profitability of innovative biological preparations and the importance of their use in agriculture have been demonstrated.

Key words: potato, biocontrol, beneficial microorganisms, system dynamics, scab, rhizoctonia, economic simulation

JEL codes: D22, O13

INTRODUCTION

Potato is the fourth most cultivated consumption crop in the world after wheat, maize, and rice [Saber et al. 2015, Wang et al. 2019, Cui et al. 2022, Feng et al. 2022, Sabhikhi and Hunjan 2022, Vilcacundo et al. 2020]. Therefore, it is fundamental for global food security [Wahyuni et al. 2018, Shuang et al. 2022], as well as the food security of specific nations, such as China [Cui et al. 2022], India [Rich and Dizyee 2016], and Indonesia [Baihaqi et al. 2020], which alone represent more than one third of the global population.

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Potato production is plagued with widespread diseases, such as blight, bacterial wilt, dry and wet rot, rhizoctonia and scab. Multiple methods are applied to minimize their negative impact, and new ones are being developed, such as biocontrol – the use of organisms that could complement or even substitute some of the existing potato plant-protection methods. Potato biocontrol is based on beneficial microorganisms, i.e., bacteria and fungi [e.g., Vilcacundo et al. 2020]. Despite some successes, potato biocontrol is not widespread in the commercial market, as the outcomes from controlled laboratory trials have shown more satisfying outcomes than field trials. Similar outcomes were found in our experiment. Yet, as one of the tested potato varieties (Pasja Pomorska) has shown potential, we have simulated potential economic outcomes from the application of the biocontrol of this variety in the ecological field.

OBJECTIVES

There are two primary goals of this article. First, as biocontrol for potatoes has not yet made its way from the laboratories to the markets [Montesinos 2004, Mejdoub-Trabelsi et al. 2022, Vongati et al. 2022], thus being of limited access to farmers [Pathak et al. 2017], the economic viability of such experiments is assessed, calculating the potential profits and expenses for farmers. Second, as for the environmental pollution concerns [Vilcacundo et al. 2020, Meng et al. 2022], and new upcoming requirements for production in the EU countries (25% of the farm's production should be ecological), the demand for biological plant protection (biocontrol agents or microbial pesticides) and growth enhancement (biostimulants or microbial fertilizers) may gain momentum [Gitner et al. 2022], making the case for the economic assessment even more relevant. Even though the EU has encouraged the usage of biocontrol since 2009 [Vilcacundo et al. 2020], the upcoming institutional arrangement is going to demand certain behavior amendments from farmers. Moreover, most of the research concerning biocontrol agents is performed in the biological sciences, such as biotechnology, microbiology, genetics, chemical engineering, pathology, or phytopathology. While these are primary to economics regarding the effectiveness of these microorganisms, to assess the economic utility of these methods, economic research must follow.

The article is ordered as follows. First, the economic features of potato production are described as the background for the further economic model construction. Second, the economic model of potato production and sales is developed using a system dynamics (SD) method. Third, the application of biocontrol for the two potato plant diseases – scab and rhizoctonia – tested in the model are described, in separate subsections for each disease and with a summary following it. Fourth, the model simulation is performed and concluded, and recommendations for the further research are suggested.

METHODS AND DATA SOURCES

To build a properly functioning model, a literature review was conducted that focused on three main areas:

1. The economic aspect of potato production, focusing on the methods used for its assessment, including the economic aspects of pest control (here: own-price elasticities of the pesticides and fungicides). Moreover, as the underlying reason for biocontrol research is to reduce the impact of disease, and the primary goal of the research is the economic assessment of this practice, the aspect of the economic utilization of the wasted potatoes in a waste biogas plant was considered;
2. A description and comparison of the two studied potato diseases (scab and rhizoctonia) and the development of the biocontrol methods in this field;
3. A review of the studies that apply the system dynamics method to potato production modeling.

The data for the research was gathered by the Plant Breeding and Acclimatization Institute, National Research Institute in Bonin in the West-Pomeranian voivodeship (north-west Poland). The potatoes were planted in six fields (Table 1), which were subject to different treatments (or none). From the outcomes of these plantings, simulation data was extracted and simulated for the most promising potato variety, i.e. Pasja Pomorska (Pomeranian Passion).

The gathered data was simulated using the system dynamics method. System dynamics is a technique that helps to recreate the structure of systems and test the possible outcomes [Herrera et al. 2022]. In other words, it makes it possible to predict the outcomes of particular fragments of complex systems, or of the complex systems as a whole [Baihaqi et al. 2021]. Some research supplements the potato farm profit with Monte Carlo simulations [see: Rich and Dizyee 2016, Herrera et al. 2022]. Similar to our research, other SD simulations are based on case studies [see: Rich and Dizyee 2016, Herrera et al. 2022]. SD applies Causal Loop Diagrams, which create a more complex system by overlapping each other (Fig. 2). In our study, there is one such diagram, which repeats fragments of the model created by Herrera et al. [2022], i.e., the system indicators provision (including such elements as potato production, cultivation area, production inputs, etc.).

Assessment of the economic viability of the potato production

The main factors impacting the revenue in the potato production are the yields and prices [Bombik and Wolska 2004]. The levels of the former can be impacted by the weather, soil quality, and the agrotechnique used, thus in Poland the production volatility is relatively high, with higher price risk, and decreasing competitiveness of potato production. The levels of the latter consequently depend on the yields (the lower the supply, the higher the price), as well as the costs associated with the production (seed tubers, fertilizers, pesticides, etc.) [Bombik and Wolska 2004]. Moreover, any reduction due to the impact of disease has to be justified by a corresponding increase in healthy production [Zarzecka and Gugała 2010]. The potato yield also increases with the size of the field [Bombik and Wolska 2004], as suggested by economies of scale. To measure the profitability of potato production, the main methods used are the gross surplus measurement and differential calculations [Zarzecka and Gugała 2010]. For the evaluation of a biocontrol, the main indicators used are the growth enhancement and control of the disease [Cui et al. 2022].

Potatoes are the basic staple food in many countries [Wahyuni et al. 2018]. With the prospective population increases, the demand for them is likely to increase [Rich and Dizyee 2016, Hakim and Perdana 2017]. Other future pressures on potato demand include a lack of arable land to expand production, diminishing growth of yields, and climate change [Rich and Dizyee 2016, Piwowar 2018]. The quantity of potato production may also further decrease, as during the season, the risk of pest attack increases [Baihaqi et al. 2021].

The rates of potato production, and the demand for them (due to their changing price), can also be influenced by the input costs, such as pesticides. Based on the meta-study on pesticide elasticity by Böcker and Finger [2016], the median demand elasticity in Europe is –0.3, with variability among studies equal to 0.3 (Fig. 1), thus showing the inelasticity of demand

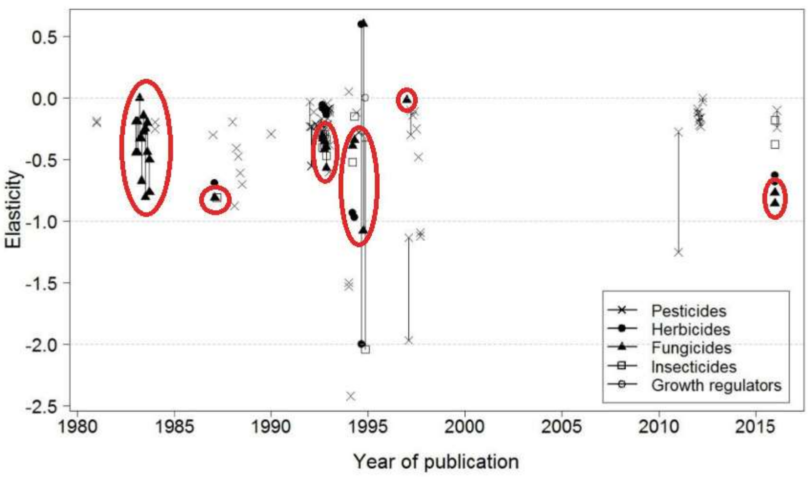


Fig. 1. Pesticide's own-price elasticities of demand following the year of publication. Fungicides are circled in highlights

Source: [Böcker and Finger 2016], own highlights – own elaboration for such products. It shows that there is a demand for such products – regardless of changes in the price – as well as their substitutes, such as biocontrol. The potential demand for biocontrol could increase if pesticides are taxed, as is already the case in several EU countries [Böcker and Finger 2016], and as is suggested by some researchers, due to the damage pesticides cause to the soil biome and pollinators [Piwowar 2018].

Potatoes that are not fit for human consumption can still be economically utilized. According to UNECE (2017), some potatoes damaged by disease can be used for human consumption, while those that are unfit can be used as animal feed or to produce ethanol or biogas. As even diseased potatoes can often be consumed by people, some research has reported a low level of potato harvest losses [Tuka 2016, Jaiswal et al. 2022]. According to calculations presented by Tuka [2016], 8% of the potato harvests in Poland consist of losses, while in a study by Jaiswal et al. [2022], on-farm operational losses reach up to 5.84% (over 70% of total losses), while disease-caused losses account for 0.15%. The majority of potato loss (28%) in Switzerland [Mack et al. 2016] is used as animal feed (90%), while 3–8% is used for biogas production, and ca. 5% ends up in waste. Some, which may contain contaminating diseases, might be destroyed to limit the possibility of leakage to the environment and further spread. For this reason, all diseased potatoes in the model were assumed to be sold for the production of the biogas.

Potato scab and recent treatment methods, including biocontrol

Scab can be identified by the occurrence of small, cork-like holes on the surface of the potatoes [Yuan et al. 2019, Feng et al. 2022, Isayenka et al. 2022, Sabhikhi and Hunjan 2022]. It is one of the most widespread potato diseases in the world [Yuan et al. 2019, Wang et al. 2019, Feng et al. 2022, Isayenka et al. 2022, Shuang et al. 2022]; the main reason for its occurrence is recurrent soilborne Streptomyces scabiei (or scabies) bacteria [Khodakaramian and Khodakaramian 2013, Yuan et al. 2019, Wang et al. 2019, Feng et al. 2022, Isayenka et al. 2022], causing significant economic damage to producers [Feng et al. 2022, Wang et al. 2022] by lowering yields and downgrading their quality [Abdelrazek et al. 2021, Cui et al. 2019, Khodakaramian and Khodakaramian 2013, Yuan et al. 2019]. The latter is especially economically severe for potato producers [Sabhikhu and Hunjan 2022].

Since the second decade of the 21st century, new methods of scab treatment have been developed. Many of them consist of gene mapping for disease-resistance, i.e. developing disease-resistant potato varieties [Khodakaramian and Khodakaramian 2013, Yuan et al. 2019], or biocontrol agents, i.e. the application of microorganisms which support disease resistance [Cui et al. 2022] and yield increase.

Scab is a disease which is difficult to contain, as it spreads through the soil and seed potatoes. The increase in the incidences of the spread of scab is due to the fast development of the potato industry [Cui et al. 2022, Shuang et al. 2022], making it a victim of its own success. The disease is mostly widespread in the potato-growing regions [Shuang et al. 2022], but its occurrence also depends on the distribution of the pathogen and its interaction with tubers, and on environmental factors, such as the pH of the soil, moisture [Yuan et al. 2019, Abdelrazek et al. 2021, Cui et al. 2022, Feng et al. 2022], microbial content of the soil [Yuan et al. 2019], crop rotation [Khodakaramian and Khodakaramian 2013, Abdelrazek et al. 2021, Cui et al. 2022, Feng et al. 2022, Sabhikhi and Hunjan 2022] or leaving the land fallow [Sabhikhi and Hunjan 2022], strain resistance and health of the seed tubers [Abdelrazek et al. 2021, Feng et al. 2022, Sabhikhi and Hunjan 2022], and use of organic or chemical treatment [Khodakaramian and Khodakaramian 2013, Abdelrazek et al. 2021,]. This multiplicity of factors makes scab management more problematic [Yuan et al. 2019, Isayenka et al. 2022].

There is neither a potato variety fully resistant to scab [Isayenka et al. 2022], nor chemical or biological controls that can fully eradicate it [Feng et al. 2022, Sabhikhi and Hunjan 2022]. Depending on the source, some authors claim that the development of scab-resistant varieties is more effective [Isayenka et al. 2022], while others point toward chemical and biological (biocontrol agents) solutions [Sabhikhi and Hunjan 2022]. Others [Cui et al. 2022, Shuang et al. 2022] distinguish between chemical and biological potato plant protection against scab, pointing toward the latter as being more friendly toward the environment, plants, people, animals, and microorganisms, and not leading to drug resistance. This might possibly lead to phasing out chemical pesticides [Shuang et al. 2022, Mejdoub-Trabelsi et al. 2022]. This recognition gave way to microbial biocontrol research [see: Wang et al. 2019, Cui et al. 2022, Feng et al. 2022, Sabhikhi and Hunjan 2022, Shuang et al. 2022], to a large extent to research on the Bacillus microorganisms [Meng et al. 2022]. Their impact has been recognized, as these bacteria not only act as pesticide, but as a fertilizer as well [Wang et al. 2019]. Although the research outcomes are promising, the precise mechanism of the biocontrol is still not entirely understood [Wang et al. 2019, Abbas et al. 2022, Cui et al. 2022, Isayenka et al. 2022].

Potato rhizoctonia and recent treatment methods, including biocontrol

Rhizoctonia solani is a disease which appears worldwide, causing canker and black scurf on the infected potatoes, reducing the quantity and especially the quality of the yield [Saber et al. 2015, Mejdoub-Trabelsi et al. 2022] and is responsible for up to 50% of economic losses in the potato industry [Mejdoub-Trabelsi et al. 2022].

Some researchers point toward the breeding of disease-resistant varieties as an effective method against it [Abbas et al. 2022], as well as controlling for pH, moisture, and temperature [Saber et al. 2015]. Depending on the research and the geographic location of the experiment, the effectiveness of fungicides is inconclusive, with some claiming its effectiveness [Abbas et al. 2022], while others denying it [Mejdoub-Trabelsi et al. 2022]. Other tested methods, such as treatment of seed tubers, crop rotation, and chemical control, are not sufficiently effective in combating it [Saber et al. 2015, Larkin and Brewer 2020, Abbas et al. 2022, Mejdoub-Trabelsi et al. 2022]. Mejdoub-Trabelsi et al. [2022] claim that crop rotation is altogether an ineffective method of fighting rhizoctonia. Larkin and Brewer [2020] compliment crop rotation with biocontrol and present it as an efficient alternative to the previous methods of combating potato diseases, although they recognize that crop rotation can have mixed effects on disease suppression, depending on what kind of plant was planted before potatoes. Since the second and third decades of the 21st century, new biocontrol methods have been being developed to combat this disease, which are based on the application of beneficial microorganisms.

Depending on the research, biocontrol can reduce the rhizoctonia by 30–60% [Larkin and Brewer 2020] or reduce the symptoms by 22.3–39.9% [Saber et al. 2015], by 15–62.6% [Khodakaramian and Khodakaramian 2013], or by 4–6 times [Abdelrazek et al. 2021]. Similar to biocontrol agents, biostimulants increased the share of marketable potato yield from 78.3% to 89.6% [Gitner et al. 2022]. This high success rate might be the consequence of their controlled trials, i.e. the experiments cited in this paragraph were performed in greenhouses.

Rhizoctonia and scab treatment with bioagents – common points

Both diseases have a global spread, and both might be the most damaging for the global potato production overall. The methods applied so far to curb them have not proven to be sufficiently effective. Thus, multiple studies have been conducted in the search for alternative pest control methods. Bioagents show some positive impact in combating both of the common potato diseases of rhizoctonia and scab. Larkin and Brewer [2020], although focusing on rhizoctonia, recognize the positive impact of biocontrol on the treatment of scab as well. Similarly, as with scab treatment, Bacillus microbes are most often cited as most effective against rhizoctonia [Saber et al. 2015, Larkin and Brewer 2020], while others [Abbas et al. 2022] point toward Trichoderma, which was also used for scab treatment in some research.

As in the case of scab, biocontrol not only inhibits the expansion of the disease, but also increases yields [Saber et al. 2015]. We confirmed such outcomes for one of the potato varieties tested in our experiment, i.e. Pasja Pomorska. The explanation offered by Saber et al. [2015] could explain the effective performance of only this variety, i.e. that biocontrol performs better in controlled, laboratory conditions than in the outdoors, due to the environmental differences. Only a few of the biocontrol agents have been developed into commercial products, thus supporting the potato production industry [Mejdoub-Trabelsi et al. 2022, Vongati et al. 2022], even though increased development of this industry can be reported beginning in the 2020s [Meng et al. 2022]. The infant level of development may explain this. Vongati et al. [2022, p. 3] also mentions "short shelf life, susceptibility to environmental conditions, expensive production systems and efficacy problems," while legislative obstacles due to the lack of scientific evidence of their efficiency, biosafety or bioterrorism were previously a concern [Montesinos 2004], but currently they are considered not harmful for people and the environment [Pathak et al. 2017]. This shows a clear research gap for the modeling of the economic viability of such products.

System dynamics in potato production

SD has been applied to several papers focusing on potato production. While some are focused on production methods [DeFauw et al. 2012], seasonal production forecasts [Wahyuni et al. 2018], pest control [Pacilly et al. 2016], or potato supply chain management [Hakim and Perdana 2017], others focus on scenarios that might support policy-building [Baihaqi et al. 2021, Herrera et al. 2022, Rich and Dizyee 2016], or the positive impact of cooperatives on the potato supply chain and farmers' income [Baihaqi et al. 2021, Hakim and Perdana 2017, Herrera et al. 2022]. SD is frequently used among Indonesian researchers [Hakim and Perdana 2017, Wahyuni et al. 2018, Baihaqi et al. 2021].

As Herrera et al. [2022] states, the goal of SD is to discover the influence of feedback loops on the behavior of the system. Therefore, to fully understand the potential of the returns made possible by the researched methods, the following iterations of potato seeding should be performed (i.e. plantings). As the future is unknown and can only be estimated, several alternative scenarios can be tested. SD is seen as a useful tool for executing such scenarios. As the final model was limited to two scenarios – biome application and no fertilizer, and no pesticide use, both for the Pasja Pomorska variety – the only additional expense is the cost of the biocontrol agent itself. In our research, the first round of seeding was repeated virtually in software, so was based on a single trial. This trial was repeated 100 times. The first 30 repetitions can be seen in Table 7. As Rich and Dizyee [2016] highlight in their technical description of SD, the future behavior of the system can be simulated.

Data and model preparation

A one-year (2022) field study was conducted in a research facility in Bonin, in north-western Poland. The potato tubers were planted in six separate fields. Each field was subject to a different type of treatment, all of which are presented in Table 1. As is further justified, the biological agent was only applied to the last plot of land (number 6).

This study aimed to construct a model that will: 1) identify the cash flow of a potato farmer, 2) model potential outcomes of the potato farming, given six different conditions (i.e. six different scenarios). After the initial research, scenarios 1 and 6 were selected for the modeling as their comparison made a viable economic assessment of the biocontrol agent possible. Based on the previous research, the process by Hakim and Perdana [2017], as described in

Table 1. Six scenarios/experiments conducted in Bonin research facility in Poland

No.	Scenario/plot description
1	No fertilization or chemical protection [0/0/0]
2	Fertilization, without chemical protection [1/0/0]
3	No fertilization, with chemical protection [0/1/0]
4	Fertilization with chemical protection [1/1/0]
5	No fertilization or chemical protection + EcoStyle product [0/0/2]
6	No fertilization or chemical protection + microbial biocontrol consortia [0/0/3]

Source: own research, data obtained from the Plant Breeding and Acclimatization Institute – National Research Institute

Table 2. Potato production value chain, based on studies modeling its value chain using SD

Process	[Hakim and Perdana 2017]	[Rich and Dizyee 2016]
1	Input supply	Planting
2	Production	"Potatoes in field"
3	Harvest	Harvesting
4	Post-harvest	Sale (60%; 40% is "stored for seed lost, processed, consumed on-farm" so not accounted for in the model)
5	Marketing	N/A – not accounted for in the model

Source: own study based on Hakim and Perdana [2017] and Rich and Dizyee [2016]

Table 2, was included in the model, excluding the marketing cost.

Further, the impact of the diseases on yields was assessed. First, the averages of all the plots were collected in one table and converted into the percentage subject to pest damage (Table 3). The following conclusions were made from this initial assessment:
- potatoes fertilized and treated with pesticides have the highest yields, at least twice the average of the other crops,
- the higher the yield, the higher the disease incidence, which might be related to the density of the potatoes in the ground,
- the bioagent produced a lower yield than potatoes not fertilized and not treated with a pesticide at all.

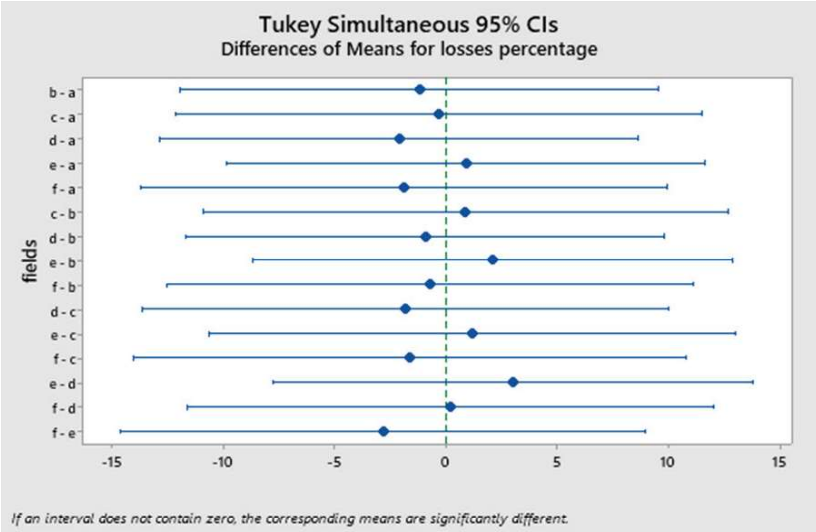
Based on the collected outcomes, the fields were further investigated according to the particular potato variety. Each field contained an identical set of varieties (Atol, Bihoro, Brda Stara, Danuta, Desire, Jelly, Kama, Krab, Pasja Pomorska, Rudawa, Saldo). Further comparisons have shown that the biocontrol substantially increased the yields and decreased the level of disease for the Pasja Pomorska variety. To check the differences of the means in different fields, a Tukey's range test was performed.

The Tukey's test is performed to check the distance between the means of different data sets. The differences between the losses in the different fields (a–f) are compared below. As can be seen below, field "f" (field on which biome was used instead of pesticides, and where fertilizers were not applied) shows all the lowest averages compared to the other fields (including of the "d–c" difference), showing that the percentage losses for field "f" were the lowest compared to all the other fields.

Table 3. Average tuber yield weight (average of 3 replicates), weight of diseased tubers by observed disease as a percentage. All variants and means.

Field	Total yield [kg]	Blight [%]	Wet Rot [%]	Dry Rot [%]	Rhizoctonia [%]	Scab [%]
1	2.9991	0	0.06	0.12	19.25	30.34
2	4.1782	0	0.04	0.35	14.80	29.83
3	4.8364	0	0	0.04	13.40	34.62
4	8.0600	0.33	0.48	0.85	7.68	32.19
5	3.8455	0	0.35	0.19	10.02	42.88
6	2.2118	0	0	0.04	18.91	24.29

Source: own calculation, based on the data obtained from the Plant Breeding and Acclimatization Institute – National Research Institute



Source: own research, based on data obtained from the Plant Breeding and Acclimatization Institute, National Research Institute in Bonin

Moreover, it could have been compared with the ecological field "a" (meaning that no fertilizer or pesticide was applied there), as both fields for this variety were only infected by two diseases, i.e. scab and rhizoctonia. Also relevant is that these two diseases are shown to be the most damaging for all fields.

Model structure

The initial examination of the data showed that a viable comparison can be drawn only for one of the varieties. Similar to the biocontrol research of Wang et al. [2019], the selected fields were not treated with any chemical material (fertilizers, pesticides, etc.). The variety whose growth can be supported by the biome is Pasja Pomorska (eng. Pomeranian Passion) which, overall, is a variety typically delivering substantial yields (see Table 4).

When comparing the ecological production where neither fertilizers nor pesticides were used with the production in which the biome was applied, other factors have to be accounted for, such as:

- loss rate (diseased potatoes sold for an alternative use, e.g. biogas production, which helps to partially redeem the financial loss)
- potato market price (the price elasticities of demand were not accounted for)
- diesel consumption (as for the "no fertilization or pesticides" method, there was no diesel consumption. It has to be checked whether diesel expenses would make the biome application less financially viable. Finally, the diesel price for the bioagent application was not included, as it can be performed at the same time as harrowing)
- price of the biome itself

Table 4. Cultivation of Pasja Pomorska using ecological methods (no fertilization, no pesticides; and biome application).

	Weight of potatoes [kg]		Relation between healthy and infected potatoes [%]	
	Healthy potatoes	Infected potatoes	Healthy potatoes	Infected potatoes
No fertilization, no pesticides	2.72	2.57	51.42	48.58
Biome application	3.77	2.55	59.65	40.35

Source: Plant Breeding and Acclimatization Institute – National Research Institute

As reported by Gitner et al. [2022], the highest costs in the potato cultivation were labor, fertilizers and seed tubers. As seed tubers were used from the preceding season in our calculations (see Table 5 and Figure 2), they were not accounted as an expense. As fertilizer was not used (as much as biocontrol is not a fertilizer *per se*), and the planting used manual labor, these factors were also not accounted for. The main intention of the two simulations was to show the difference in costs, as well as potential gains in yields. The model does not account for the inflation rate or the elasticities of fertilizers and plant protection, as from the data examination, no fertilizer and pesticide-supported varieties were selected. All the formulas can be seen in Table 5. Before applying the data to the model, it was accordingly recalculated for the plot size of 1 hectare, as the experimental plots were of size 0.0237 hectare.

Table 5. Formulas and data included in the model

Name of a variable	Calculation/Formula	Data source	Inclusion justification
Yield	30×0.03×42; Field-Potatoes for sale	Research facility in Bonin	Seed tubers per hectare
Field	[Plot 1 or 6 yield]×Yield (based on Table 6)	Research facility in Bonin	To obtain a full hectare
Loss	Field×(Rhizoctonia+Scab)	Research facility in Bonin	Subtraction of wasted potatoes
Rhizoctonia	Differs for both scenarios (based on Table 6)	Calculated from Bonin data	Occurring disease in [%]
Scab	Differs for both scenarios (based on Table 6)	Calculated from Bonin data	Occurring disease in [%]
Utilization	Waste price×Loss	Outcome	Loss minimization
Waste price	0.4 [PLN/kg]	Based on data found online	Price of wasted potatoes
Healthy yield	Field-(Rhizoctonia+Scab)	Outcome	Yield for human consumption
Potatoes for sale	Healthy Yield	Outcome	Included for modeling reasons
Potato price per kg	Yield×1 [PLN/kg]	Based on data found online	Yield times price
Potato sale minus inputs	Potato price per kg-Biome cost	Outcome	Revenue minus cost
Biome cost	700 [PLN/ha]	Research facility in Bonin	Cost of the bioagent
Income	Utilization+Potato sale minus inputs	Outcome	Model outcome

Source: own study

Table 6. Yields and disease ratios for the two chosen scenarios

Technique	Weight of tubers [kg]		
	Total Yield	Rhizoctonia	Scab
No fertilizer or pesticide	5.29	2.15	0.42
Biome	6.32	2.42	0.13

Source: data obtained from the Plant Breeding and Acclimatization Institute – National Research Institute

As the experiment has shown, Pasja Pomorska is not affected by the following diseases, which were infecting the other varieties: blight, wet and dry rot. It was still affected by rhizoctonia and scab.

RESULTS AND DISCUSSION

The data presented in this research is modeled through the technique of system dynamics. Six experiments were conducted, which were used as a proxy for the farmers' expenses versus returns simulations. The examination of the original and simulated data confirmed that biome would not produce a higher yield than potatoes cultivated using conventional methods, so the simulations were limited to two scenarios ("no fertilizer or pesticide" and "biome") on the most promising potato variety, which was Pasja Pomorska. The gross surplus measurement was calculated for both scenarios [Zarzecka and Gugała 2010], focusing on the main factors of potato production, i.e. yield and price, with the addition of the justified costs (focusing on the role of the bioagent in the profit creation) and recognition of the field size [Bombik and Wolska 2004, Zarzecka and Gugała 2010]; as well as both growth enhancement and control of disease [Pathak et al. 2017, Cui et al. 2022], which help to measure and analyze the benefit of the biocontrol usage. The integrated model is presented in Figure 2.

The model starts its simulation with 30 tubers of Pasja Pomorska (after finishing a planting cycle, it accumulates in the stock called Yield), which produces a yield in the "Field." The potato outcome is then split into two components: one is healthy potatoes ("Healthy Yield"), and infected ones ("Loss"). The rate of infection was calculated previously and is shown in Table 7. Losses are sold for biogas digestion (0.4 PLN/kg), while healthy potatoes are sold wholesale (1 PLN/kg). These are later accumulated in the stock called "Income." The cost of the biome and diesel are only subtracted from the "Biome" scenario (see: Figure 3, blue line). These costs are subtracted from the sale of consumption potatoes (but could also be subtracted from the final "Income").

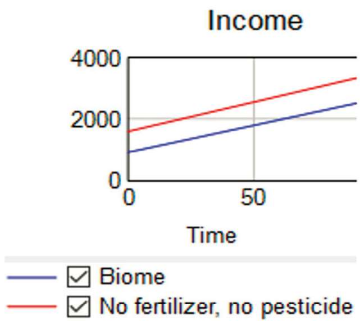


Fig. 3. Graph depicting the outcome of the two simulations
Source: VENSIM, an outcome of the simulation. Own study

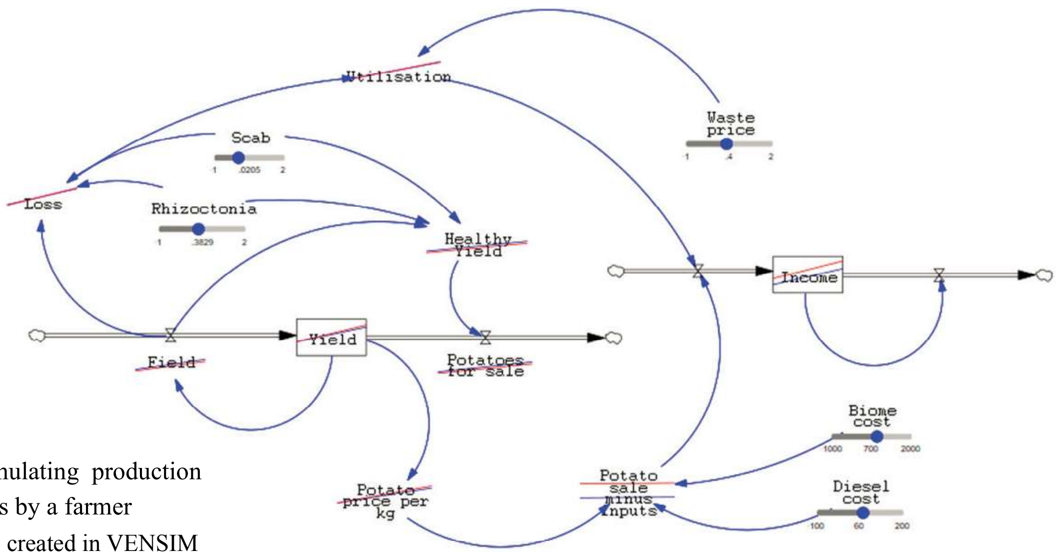


Fig. 2. Model simulating production and sale of potatoes by a farmer
Source: own model, created in VENSIM

Table 7. Differences between financial viability (Income) for farmers, for the scenarios of sole biome usage, and no plant protection, and no fertilizer usage

Time	Biome	No fertilizer or pesticide	Ratio
0	896.827	1580.75	1.763
1	914.508	1599.96	1.750
2	932.19	1619.17	1.737
3	949.872	1638.38	1.725
4	967.553	1657.58	1.713
5	985.235	1676.79	1.702
6	1002.92	1696	1.691
7	1020.6	1715.21	1.681
8	1038.28	1734.41	1.670
9	1055.96	1753.62	1.661
10	1073.64	1772.83	1.651
11	1091.32	1792.04	1.642
12	1109.01	1811.24	1.633
13	1126.69	1830.45	1.625
14	1144.37	1849.66	1.616
15	1162.05	1868.87	1.608
16	1179.73	1888.07	1.600
17	1197.41	1907.28	1.593
18	1215.1	1926.49	1.585
19	1232.78	1945.7	1.578
20	1250.46	1964.9	1.571
21	1268.14	1984.11	1.565
22	1285.82	2003.32	1.558
23	1303.5	2022.53	1.552
24	1321.18	2041.73	1.545
25	1338.87	2060.94	1.539
26	1356.55	2080.15	1.533
27	1374.23	2099.36	1.528
28	1391.91	2118.56	1.522
29	1409.59	2137.77	1.517
30	1427.27	2156.98	1.511

Source: VENSIM, outcome of the simulation. Own study

As for the Pasja Pomorska variety, while the yields are better for the biome (both quantity and quality), with the assumed prices (PLN 6 per liter of oil and consumption of 10 liters per hectare, PLN 700 per biome per hectare, 40 grosz per kg of potatoes for biogas, and 1 PLN per kg of consumption potatoes), it still works out less profitable than for the "no fertilizer or pesticides" variant. This was because with this variant, there was no additional cost of 700 + 60 PLN for planting (biome and diesel, respectively).

The biome would have to cost around 150 PLN to be profitable, instead of 700; or alternatively, if the biome treatment were performed during other activities, such as harrowing, the biome should cost ca. 210 PLN. As shown in Table 7, the financial "distance" between both selected trials would diminish over time, which was the function suggested by the software itself. Alternatively, the consumption price for such potatoes could be increased.

Similar to what was described by Wang et al. [2019], the decrease of the disease impact was not high enough. Wang et al. [2019] report that in field conditions, the reduction of the disease impact with the biocontrol agents was 8.8%, while in trials in controlled experimental conditions, it was 36.7% and 51.4%. The impact of the environment may account for this underperformance of biocontrol agents in field conditions as compared to chemical treatments.

Conclusion, recommendations and limitations

The methods that were chosen for the further assessment were extensive [Bombik and Wolska 2004] – i.e. no chemical fertilization or plant protection were used on the chosen fields. Extensive methods have shown the most promising outcomes for the further economic assessment, despite the overall higher yields of the intensive methods [Bombik and Wolska 2004], as well as the higher direct costs of the extensive (or ecological) farming [Zarzecka and Gugała 2010]. Despite that, farmers – especially in the EU – might consider turning toward bioagents as they will soon face new institutional arrangements and requirements. The European Green Deal demands that farmers set aside 25% of their production for ecological production. This increases the possibility of wider biome use by farmers. With economies of scale, the sales price of the biome should also decrease. Moreover, special focus should be put on research into the impact of biome on the protection of potatoes from two diseases: rhizoctonia and scab.

As the testing of biome continues, we recommend adding to the model:
- potato price elasticities, which could react within the model to the estimated inflation rates,
- possibility of the establishment of an EU-wide pesticide tax, thus increasing the economic viability of the application of biome in other potato varieties,
- differences in the resistance to extreme weather events,
- further research on the soil composition and mineral depletion, comparing conventional methods (fertilizers and pesticides) with biome,
- impact of the European Green Deal.

Some limitations to this study can be identified. As there is only one set of outcomes from the field experiment (i.e. from one season of potato planting), the research should be followed up and expanded with repeated trials in the future, to confirm the current findings.

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OCENA EKONOMICZNA WYKORZYSTANIA PREPARATU BIOLOGICZNEGO W EKOLOGICZNEJ PRODUKCJI ZIEMNIAKA – SYMULACJA DYNAMIKI SYSTEMU

STRESZCZENIE

Cel: Celem pracy była ocena opłacalności ekonomicznej poprzez obliczenie potencjalnych przychodów i kosztów dla rolników, jak również symulacja wpływu ekonomicznego, zastosowania środka mikrobiologicznego w uprawie ziemniaka w ramach doświadczenia polowego. Doświadczenie polowe miało na celu określenie roli środka mikrobiologicznego w uprawie ziemniaka jako zastępującego syntetyczne nawozy oraz środki ochrony roślin. **Metody:** Do symulacji wykorzystano dane z jednorocznego eksperymentu polowego, które przeanalizowano za pomocą metody dynamiki systemowej. Z jedenastu testowanych odmian na sześciu różnych poletkach doświadczalnych wybrano jedną najbardziej ekonomicznie opłacalną odmianę – Pasja Pomorska. Zastosowano podejście komparatystyczne do przedstawienia wyników inokulacji roślin ziemniaka czynnikami biologicznymi w porównaniu do stosowania syntetycznych pestycydów i nawozów. **Wyniki:** Wyniki badań wskazują, że zastosowanie środków biokontrolnych zwiększa jakość i ilość plonu ziemniaka w porównaniu z wariantem, w którym nie stosuje się środków syntetycznych. Są one jednak wyższe przy zastosowaniu tych ostatnich. Stwierdzono, że czynnik mikrobiologiczny mógłby wspierać ekologiczną produkcję ziemniaka, jednak jak dotąd nie osiąga ona zadawalającego ekonomicznego progu opłacalności. **Wnioski:** Mając na uwadze organiczenia wynikające z eksperymentalnego charakteru badań polowych, wykazano poziom ekonomicznej opłacalności innowacyjnych preparatów biologicznych oraz znaczenie ich zastosowania w rolnictwie.

Słowa kluczowe: ziemniak, biokontrola, pożyteczne mikroorganizmy, dynamika systemu, parch, rizoktonioza, symulacja ekonomiczna