THE MOST IMPORTANT POTATO DISEASES AND MICROBIOLOGICAL AGENTS FOR THEIR CONTROL: A REVIEW

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Abstract
Following the regulations of the European Union ʽFarm to Fork Strategy' encourages a significant reduction in the use of plant protection products and mineral fertilizers by 2030. Potatoes are grown widely because they are a valuable source of nutrition. However, achieving high levels of yield and quality remains a challenge, particularly due to the risk of diseases. The causal agents of diseases belong to various kingdoms – fungi, bacteria, and viruses. The potato late blight (caused by *Phytophthora infestans*), early blight (caused by *Alternaria* spp.), black scurf (caused by *Rhizoctonia solani*), silver scurf (caused by *Helminthosporium solani*), black dot (caused by *Colletotrichum coccodes*), fusarium dry root (caused by *Fusarium* spp.) and common scab (caused by *Streptomyces* spp.) are the most important potato leaf and tuber diseases. The market offers a wide variety of microbiological products, which contain microorganisms for the control of potato diseases. The active ingredients in these products are primarily microorganisms from the fungal and bacterial kingdoms, such as *Bacillus* spp., *Trichoderma* spp., *Pseudomonas* spp., or their combinations. However, they differ in effectiveness against pathogens, as well as in the timing of application, the number of applications, the form of the products, and the most favorable meteorological conditions during and after treatment. It has a future and potential to be a good alternative to chemical plant protection. The aim of this study was to summarize information from researches about the popular microbiological products, their component biology and effectiveness to control potato diseases.
Keywords: *Solanum tuberosum* L., potato diseases, *Bacillus* spp., *Trichoderma* spp., *Pseudomonas* spp.

Introduction

Potato (*Solanum tuberosum* L.) is the most widely cultivated and one of the major tuber crops in the world. It is ranking third to fourth place among the most cultivated crops, following wheat (*Triticum aestivum*), rice (*Oryza sativa*) and sharing place with maize (*Zea mays*) (Simko, 2004; Kumar & Chandra, 2018; Campos & Ortiz, 2020). One of the main challenges in growing potatoes is the impact of diseases and pests, which can significantly affect plant development.

Another major issue is the low availability of nutrients during the early stages of growth (Finckh et al., 2006). Potato yields worldwide show a significant difference between conventional and biological growing systems, with yield gaps typically ranging from 9% to 25%, and in some cases reaching as high as 70% (Ierna & Parisi, 2014; Wilbois & Schmidt, 2019; Zarzyńska et al., 2023). This variation is strongly influenced by factors such as diseases and pests and the timing of disease development. Other factors that may influence the yield difference include the growing conditions of the year, lack of irrigation, and other cultivation technologies (De Ponti et al., 2012).

Due to the increasing spread of plant diseases and pests, farmers are using chemical plant protection products with greater frequency.

However, the European Union's 'Farm to Fork' strategy encourages a major reduction in the use of plant protection products and mineral fertilizers by 2030 (European Union, 2020). Over the past 20 years, global demand for pesticide-free food has grown, driven not only by concerns for human health but also by the desire to reduce environmental risks (Basu, 2009).

Microorganisms play a crucial role in reducing the use of chemical pesticides in agriculture. These organisms can promote plant growth and development, increase crop yield and quality, decompose organic matter, fix atmospheric nitrogen, and convert it into a form that is easily absorbed by plants and reduce or limit the spread of plant pathogens through various mechanisms (Marjanović et al., 2024).

The aims of this study were to summarize information from researches about the beneficial microbiological agents, their biology and effectiveness, as well as how it can be used in sustainable agricultural practices to control the development of common pathogens of potato diseases.

Materials and Methods

This review paper draws on scientific literature concerning microbiological plant protection products (bioagents), their suitability for use, and their impact on potato leaf and tuber diseases. The study examines the experience of various countries with registered microbiological agents and analyzes most common potato diseases, their pathogens, and control options.

Results and Discussion

The most significant and potentially damaging potato leaf diseases are late blight (caused by *Phytophthora infestans*) and early blight (caused by *Alternaria* spp.). From tuber diseases the major ones are potato black scurf (caused by *Rhizoctonia solani*), silver scurf (caused by *Helminthosporium solani*), black dot (caused by *Colletotrichum coccodes*), common scab (caused by *Streptomyces* spp.) and bacterial blackleg (caused by *Pectobacterium* spp.), as well as many *Virus* kingdom microorganisms, such potato X, Y, M, S, mop-top viruses etc. (Finckh et al., 2006; Fiers et al., 2012; Campos & Ortiz, 2020).

Potato leaf diseases

Potato late blight caused by *Phytophthora infestans* from the *Chromista* kingdom, *Oomycota* phylum, *Peronosporales* order. It is one of the most significant and destructive potato diseases in the world (Subhani, 2016). It reproduces sexually through oospores and asexually through conidia and zoospores. This allows for a wider and faster development of the infection (Nowicki et al., 2012). The pathogen survives in potato tubers, plant debris in the form of mycelium and in the soil as oospores (Andrivon, 1995). Asexual spores are transmitted by wind and water. The optimal development temperature is moderately warm, the range of 10–25 °C, with a relative humidity 90–100% (Nowicki et al., 2012; Subhani, 2016).

Potato early blight caused by *Alternaria* spp. from the *Fungi* kingdom, *Ascomycota* phylum, *Pleosporales* order. Sexual reproduction is not observed, but the high species diversity indicates extensive pathogen recombination (Schmey et al., 2024). The pathogens reproduce asexually through conidia. The fungus *Alternaria* survive and overwinter in the form of mycelium or conidia in plant debris, the soil, and potato tubers. The spores can be dispersed by wind and water, sometimes with the help of insects (Tsedaley, 2014; Yuldashova et al., 2023). The optimal weather conditions for the pathogen development are hot and humid. The quick development of conidia occurs at temperatures between 20–30 °C, with relative air humidity under 70% (Tsedaley, 2014; Escuredo et al., 2019).

Potato tuber disease

Black scurf, stem canker and root rot caused by *Rhizoctonia solani* from the *Fungi* kingdom, *Basidiomycota* phylum, *Cantharellales* order. *R. solani* survives in the form of mycelium in plant debris or as sclerotia in the soil, and spreads through infected seed material (Aydin, 2022; Nasimi et al., 2024). The optimal growth temperature for the pathogen is moderate, the range of 15–25 °C (Orozco-Avitia et al., 2013). Increased soil moisture, about 20%, is beneficial (Kiptoo et al., 2021).

Silver scurf caused by *Helminthosporium solani* from the *Fungi* kingdom, *Ascomycota* phylum, *Pleosporales* order. Initially, the fungus produces mycelium, followed by the production of conidia. The pathogen survives in infected tubers and in the soil (Avis et al., 2010; Tiwari et al., 2020). The spread of the disease starts in the soil, with the first symptoms appearing during harvest, but the pathogen continues to develop even in storage. Optimal conditions are above +3 °C with a relative humidity of 90% (Abbas et al., 2013; Tiwari et al., 2020). Maximum sporulation and the highest number of conidia are observed at +24°C and humidity 90–95% (Tiwari et al., 2021). However, the fungus can develop over a wide temperature range of 2–30 °C (Abbas et al., 2013).

Black dot caused by *Colletotrichum coccodes* from the *Fungi* kingdom, *Ascomycota* phylum, *Glomerellales* order. The pathogen survives in infected seed material and soil (Lees & Hilton, 2003; Cannon et al., 2012; Mattupalli et al., 2013; Johnson et al., 2018). Infection occurs early in the season, but visible symptoms and sclerotia begin to appear closer to harvest time (Mattupalli et al., 2013; Johnson et al., 2018). The optimal temperature for conidia growth is +22 °C, while mycelium grows best in the temperature range from 25 to 31 °C, and moist soil conditions (Lees & Hilton, 2003).

Potato common scab caused by *Streptomyces* spp. from the *Monera* kingdom, *Actinobacteria* class and *Actinomycetales* order. *Streptomyces* spp. infects tuber crops worldwide (Lerat et al., 2009; Hamedo & Makhlouf, 2013). Bacteria form structures that are morphologically similar to hyphae and spores. The mycelium is made up of hyphae, and spores being released from their ends (Braun et al., 2017). The pathogen survives in the soil, plant debris, and infected seed material. The pathogen spores can penetrate through damaged areas or lenticels (Dees & Wanner, 2012; Braun et al., 2017). The optimal soil pH for the bacterium development is slightly acidic to neutral, between 5.5 and 7.5. It infects young tubers most intensively when the temperature is above +20 °C and the soil moisture is between 65–70% or lower (Braun et al., 2017).

Microbiological agents

To achieve a high quality potato harvest, it is essential to follow a set of agrotechnical practices, primarily focused on prophylactic measures. This includes selecting the appropriate variety, implementing various cultivation technologies during the growing season, and ensuring proper storage conditions in warehouses (Tresnik, 2007). Some bacteria and fungi also have beneficial properties that can be applied in biological farming and sustainable agricultural practices. Products containing bacteria or their metabolites, enzymes, or antibiotics are frequently mentioned in the literature, such as *Bacillus* spp., *Pseudomonas* spp., *Azospirillum* spp., and *Azotobacter* spp. The most popular fungi are *Trichoderma* spp. and *Aspergillus* spp., which produce secondary metabolites.

Bacteria from genera ***Bacillus*** is gram-positive, aerobic, rod-shaped, and motile bacteria (Maughan & Van der Auwera, 2011). The most well- known species is *B. subtilis*, which produce metabolites, such as enzymes, antibiotics, and enhance the plants resistance to pathogens and pests. Other species, for example, *B. velezensis*, *B. macerans*, *B. azotofixans* etc., are known as *Plant Growth-Promoting Bacteria* (PGPB). Bacteria found in the rhizosphere can protect plants in several ways: 1) they produce volatile organic compounds that increase root exudation; 2) produce secondary metabolites that have antibiotic compounds; 3) form biofilms, colonize the roots and protect them from harmful effects of pathogens (Choudhary & Johri, 2009; Khan et al., 2022).

Bacillus spp. increase yield and improve disease resistance in most cereal grains, legumes, as well as cucumbers, tomatoes, and potatoes (Miljaković et al., 2020). There are several ways to use *Bacillus* based treatments:

1. Seed tuber treatment with a bioagent requires soaking potato seed tubers in a *Bacillus* containing solution for 20–30 minutes, and this treatment improves both yield and biomass growth (Kumar et al., 2013). Additionally, it helps reduce the development of late blight during storage after harvest (Lastochkina et al., 2022), as well as reduces the incidence and severity of black scurf under greenhouse conditions (Saber et al., 2015).
2. Seed tuber and foliar treatment. A bioagent based on talc, which is later prepared as a solution, is used. The seed tubers are treated as mentioned above, and 40 days after planting (DAP), the same solution is used for foliar spraying (Wei et al., 2024).
3. Soil and foliar treatment. *Bacillus* through soil treatment or drenching before planting potatoes is applied. Later, during the growing season, foliar spraying with the bioagent is carried out. These measures reduce the spread of late blight and improve various physiological parameters of potato plants compared to the control (Kumbar et al., 2019).

Global research is exploring various bacterial species and their interactions with pathogens, particularly focusing on the *Pseudomonas* spp., *Azospirillum* spp., and *Azotobacter* spp., which are classified as PGPB. *Pseudomonas* spp. can form biofilms, release metabolites with potent antifungal properties, synthesize phytohormones, fix atmospheric nitrogen, and facilitate nutrient decomposition and absorption (Sah et al., 2021).

In a field trial, treating potato tubers with ***Pseudomonas*** based bioagents before planting helped limit *R. solani* growth. A talc-based formulation was more effective than a *Pseudomonas* suspension, significantly reducing stem cancer and black scurf while increasing yield (Lal et al., 2022). In another study, three genera of microbiological agents (*Pseudomonas* spp., *Trichoderma* spp. and *Bacillus* spp.) showed high efficacy against *Alternaria* spp. in *in vitro* and under greenhouse conditions (Aldiba & Escov, 2019). *P. putida* shows effectiveness against *H. solani*, but the experiment was conducted only on plates (Elson et al., 1997).

For foliar disease control, multiple bioagent spray applications were necessary. A multi-year study found that applying *P. putida*, *B. subtilis*, and *T. erinaceum* eight times effectively controlled *P. infestans* for 60 days, reducing disease severity by nearly half (Islam et al., 2022).

***Azospirillum* spp.** promotes plant growth by fixing atmospheric nitrogen and producing phytohormones (Cassán & Diaz-Zorita, 2016; Fukami et al., 2018). *A. lipoferum* effectively controls potato early blight (caused by *Alternaria* spp.) in both greenhouse and field conditions. In field trials, spraying the bioagent at BBCH 15–17 reduced disease incidence by 40–50% compared to the control (Mehmood et al., 2021).

***Azotobacter* spp.** are widely known for their nitrogen fixing properties; however, they are also capable of producing antifungal substances that limit the activity of fungal pathogens near the root system (Jiménez et al., 2011; Wani et al., 2016; Sumbul et al., 2020; Al-Baldawy et al., 2023).

Microbiological products containing combinations of different microorganisms, such as *Pseudomonas* spp., *Bacillus* spp. and *Azotobacter* spp., showed the lowest development compared to the control. These bioagents, in various combinations, were applied once to the seed tuber material at the planting (Aguk et al., 2018). Seed tuber treatment with *Azotobacter* spp. may reduce the incidence of *R. solani* (Meshram, 1984).

***Trichoderma* spp**. produces secondary metabolites that enhance plant growth and development and is referred to as a plant growth promoting agent (PGPA) (Yao et al., 2023). *Trichoderma* spp. is the most widely used fungal genus in biological plant protection, accounting for about 90% of cases (Błaszczyk et al., 2014). This fungus is most commonly used as a soil disease controller, which can colonize plant roots, but it can also limit pathogens on the aerial parts of the plant – leaves, stems and spikes. *Trichoderma* interact with other pathogenic fungi: 1) by suppressing, entering the cells of other organisms, such as *Phytophthora* sp., *Pythium* sp., *R. solani*, *Colletotrichum* spp., *Sclerotinia sclerotiorum*, *Botrytis cinerea* and secreting various enzymes; 2) by competing for nutrients, such as with *B. cinerea*; 3) by producing compounds similar to antibiotics that act against pathogens, such as *B. cinerea*, *R. solani*, and *F. oxysporum* (Błaszczyk et al., 2014; Yao et al., 2023); 4) *Trichoderma* is also capable of induced systemic resistance (ISR), activate plant self defense mechanisms (Dutta et al., 2023; Yao et al., 2023).

The most common products on the market contain *Trichoderma* species such as *T. viride*, *T. virens*, and *T. harzianum* and the less commonly used species, *T. asperellum*, *T. longibrachiatum*, *T. koningii*, *T. polysporum*. These products are often available in the form of granules or powder, which are used to treat seed tuber material before sowing (Zin & Badaluddin, 2020; Yao et al., 2023). A spore solution containing bioagent was applied twice to the plants on the 15 and 45 DAP (Rakibuzzaman et al., 2021). Recent studies also examine the impact of *Trichoderma* spp. on potato early blight (caused by *Alternaria* spp.) (Metz & Hausladen, 2022).

The combination of fungus *T. harzianum* and bacteria *B. subtilis* different strains has shown high effectiveness against the potato common scab (caused by *Streptomyces* spp.). Different concentrations of bioagents were used, which were added once to the seed potatoes in the furrows (Wang et al., 2019). In another experiment against potato black scurf, bioagent *T. harzianum* showed higher effectiveness than *B. subtilis*. In this case as well, the seed tuber material was treated once before planting by soaking the seeds in the isolate solution (Khalil et al., 2019).

***Aspergillus* spp.** and ***Penicillium* spp.** both genera include beneficial and harmful microorganisms (Houbraken et al., 2020). Certain species of both genera limited the growth of *R. solani*, *P. infestans*, and *Fusarium* spp. on the plate (Lal et al., 2016; Trabelsi et al., 2016). *P. viridicatum* and *T. viride* showed high effectiveness against late blight when applied as a bioagent suspension spray 40 DAP (Gupta et al., 2004). *P. chrysogenum* is effective against early blight reducing pathogen growth in both *in vitro* and *in vivo* conditions when potato leaves were treated with the bioagent solution (Hatem et al., 2022).

Table 1 illustrates the interaction of various microbiological agents and potato disease pathogens, as well as the different methods of their application. In the table, a cross indicates which specific pathogens are affected by the bioagent.

Based on the information available in scientific publications, it is evident that various microbiological agents are used to control plant disease pathogens, with varying degrees of effectiveness. A large number of studies have been conducted under controlled laboratory conditions; however, there are relatively few field conditions studies.

Table 1

The interaction of beneficial microorganisms with pathogens and application of microbiological products

Beneficial microorganisms in microbiological products	***Pathogens***						***Notes***
	P. infestans	**Alternaria spp.**	**R. solani**	**H. solani**	**C. coccodes**	**Streptomyces spp.**	
***Trichoderma* spp.** (Aldiba & Escov, 2019; Blaszczyk et al., 2014; Islam et al., 2022; Khalil et al., 2019; Metz & Hausladen, 2022; Wang et al., 2019; Yao et al., 2023; Zin & Badaluddin, 2020)	×	×	×		×	×	A wide range of applications. Seed tuber material treatment before sowing (in-furrow treatment, soaking, spraying, etc.). Soil and leaf spraying under greenhouse conditions. Foliar spraying on 34, 41, 48, 53, 57, 62, 69 un 75 DAP*.
***Bacillus* spp.** (Aldiba & Escov, 2019; Islam et al., 2022; Kumbar et al., 2019; Lastochkina et al., 2022; Saber et al., 2015; Wang et al., 2019; Wei et al., 2024)	×	×	×			×	Seed tuber material is treated with agent shortly before planting. Leaf spraying starts from the 34 DAP.
***Pseudomonas* spp.** (Aldiba & Escov, 2019; Elson et al., 1997; Islam et al., 2022; Lal et al., 2022)	×	×	×	×			Soil and leaf spraying under greenhouse conditions. Seed tuber material treatment before planting. Leaf spraying starts from the 34 DAP *in vitro* conditions.
***Azospirillum* spp.** (Mehmood et al., 2021)		×					In field trials, leaf spraying at BBCH 15–17.
***Azotobacter* spp.** (Meshram, 1984; Sumbul et al., 2020)			×	×			Seed tuber material treatment before planting.
***Aspergillus* spp., *Penicillium* spp.** (Gupta et al., 2004; Hatem et al., 2022; Lal et al., 2016; Trabelsi et al., 2016)	×	×	×				Reduce pathogen growth on the plate. Foliar spraying at 40 DAP.

*****DAP – days after planting.

Conclusions

1. The most significant potato pathogens are *Phytophthora infestans*, *Alternaria* spp., *Rhizoctonia solani*, *Helminthosporium solani*, *Colletotrichum coccodes* and *Streptomyces* spp.
2. The most common and extensively studied microbiological agents come from the kingdoms of bacteria and fungi – *Bacillus* spp., *Trichoderma* spp.; less studied genera include *Pseudomonas* spp., *Azotobacter* spp., *Aspergillus* spp. and *Penicillium* spp.
3. The use of microbiological agents in the formulation of various products is increasing. These microbiological agents also have potential in low-input

agriculture, as they provide a good alternative to chemical plant protection products.
4. Most microbiological agents show effectiveness against potato tuber diseases; however, some microorganisms, when applied to the leaves, also demonstrate effectiveness against potato early blight and late blight. Further research is necessary, as fewer studies have been conducted under field conditions compared to *in vitro* studies, and different strains of biological agents exhibit varying levels of effectiveness against diseases.

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