

Projekttitel

SLU Partnerskap Alnarps projekt nr: 1461

Projekttitel på svenska enligt projektansökan: Testning av biologiska medel för bekämpning av potatisbladmögel och torrfläcksjuka

Projekttitel på engelska enligt projektansökan: Testing new biologicals to combat potato early and late blight

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Projektsammanfattning

Potatisbladmögel (*Phytophthora infestans*) och torrfläcksjuka (*Alternaria solani*) är två av de viktigaste sjukdomarna i potatisodling och bekämpas idag främst med upprepade fungicidbehandlingar. Samtidigt finns ett ökande behov av att minska användningen av kemiska växtskyddsmedel och utveckla mer hållbara växtskyddsstrategier. Biologiska växtskyddsprodukter har därför fått ökad uppmärksamhet som ett möjligt komplement till konventionella fungicider. Trots lovande resultat från laboratorie- och växthusförsök finns det fortfarande begränsad oberoende kunskap om hur dessa produkter fungerar under mer realistiska odlingsförhållanden.

Syftet med projektet var att utvärdera utvalda biologiska produkter mot potatisbladmögel och torrfläcksjuka, med särskilt fokus på deras effekt under semi-fält- och fältförhållanden. Fält- och semi-fältförsök genomfördes i Flakkebjerg, Danmark, med potatisplantor som inokulerades med antingen *P. infestans* eller *A. solani*. De biologiska produkterna jämfördes med standardbehandlingar med fungicider och obehandlade kontroller. Sjukdomsutvecklingen utvärderades i försöken, medan skörd, knölkvalitet och stärkelsehalt också undersöktes i fältförsöket för att få en bredare bild av behandlingarnas effekter.

Som en kompletterande del av projektet genomfördes även växthus- och laboratieförsök med utvalda behandlingar mot *A. solani*. Under kontrollerade förhållanden minskade några av behandlingarna utvecklingen av torrfläcksjuka, men effekten varierade mellan potatissorterna Bintje och Kuras. NoMo, en produkt baserad på eteriska oljor, hämmade även tillväxten av *A. solani* direkt i laboratieförsök, särskilt vid högre koncentrationer.

I semi-fält- och fältförsöken gav standardbehandlingarna med fungicider den högsta och mest stabila sjukdomskontrollen. Bland de biologiska behandlingarna visade kaliumfosfit den mest konsekventa effekten, särskilt mot potatisbladmögel, och var återigen den bäst presterande alternativa behandlingen i semi-fältförsöket med potatisbladmögel 2024. Melatonin i låg koncentration (0,1 mM) visade också lovande effekt mot torrfläcksjuka i försöket 2024. De övriga biologiska produkterna hade däremot begränsad eller varierande effekt, och den lovande effekten av NoMo som observerades under kontrollerade förhållanden kunde inte bekräftas under semi-fältförhållanden. Trots tydliga skillnader i sjukdomsutveckling var skillnaderna i skörd och knölkvalitet relativt små i fältförsöket, och behandlingarna hade ingen tydlig effekt på stärkelsehalten.

Projektet ger oberoende kunskap om biologiska produkters effekt under kontrollerade förhållanden samt under semi-fält- och fältförhållanden. Resultaten visar att lovande effekter som observeras under kontrollerade förhållanden inte alltid leder till en stabil sjukdomskontroll under mer realistiska odlingsförhållanden. Under de förhållanden som utvärderades i projektet kunde de biologiska produkterna inte ersätta konventionella fungicider, särskilt vid högt sjukdomstryck. Kaliumfosfit visade störst och mest konsekvent potential bland de utvärderade produkterna och skulle kunna användas som ett kompletterande verktyg inom integrerat växtskydd. Melatonin i låg koncentration bör också undersökas vidare för bekämpning av torrfläcksjuka.

Ytterligare försök under flera odlingssäsonger och under olika miljöförhållanden behövs för att bedöma hur stabil effekten av dessa produkter är. Framtida studier bör fokusera på att optimera dosering och behandlingstidpunkt, vidare undersöka effekten av melatonin i låg koncentration samt utvärdera kombinationer av de mest lovande biologiska produkterna med reducerade fungicidprogram. Detta kan bidra till att avgöra om användningen av konventionella fungicider kan minskas utan att äventyra sjukdomskontrollen.

Project Summary

Potato late blight (*Phytophthora infestans*) and early blight (*Alternaria solani*) are two of the most damaging diseases affecting potato production and are mainly controlled using repeated fungicide applications. As agriculture moves towards more sustainable production systems, there is increasing

interest in biological products that can reduce dependence on conventional fungicides. However, many of these products have mainly been tested under laboratory or greenhouse conditions, and there is limited information on how consistently they perform under more realistic growing conditions.

The aim of this project was to evaluate selected biological products against potato late blight and early blight, with particular emphasis on their performance under semi-field and field conditions. Field and semi-field experiments were conducted at Flakkebjerg, Denmark, using potato plants inoculated with either *P. infestans* or *A. solani*. The biological products were compared with standard fungicide treatments and untreated controls. Disease development was evaluated across the experiments, while yield, tuber quality and starch content were also assessed in the field experiment to determine the broader effects of the treatments.

Complementary greenhouse and laboratory experiments were conducted within the project to evaluate selected treatments against *A. solani*. Under controlled conditions, some of the tested products reduced early blight development, although responses differed between the potato cultivars Bintje and Kuras. NoMo, an essential-oil-based product, also directly inhibited the growth of *A. solani* in laboratory tests, particularly at higher concentrations.

Across the semi-field and field experiments, the standard fungicide treatments provided the highest and most consistent level of disease control. Among the biological treatments, potassium phosphite showed the most consistent performance, particularly against late blight, and was again the best-performing alternative treatment in the 2024 semi-field late blight experiment. Low-dose melatonin (0.1 mM) also showed promising activity against early blight in the 2024 experiment. However, the remaining biological products showed limited or inconsistent effects, and the promising activity of NoMo observed under controlled conditions was not reproduced under semi-field conditions. Although disease control differed among treatments, relatively small differences were observed in yield and tuber quality in the field experiment, and starch content was not affected by the treatments.

The project provides independent information on the performance of biological products across controlled, semi-field and field conditions. The results show that promising effects observed under controlled conditions do not necessarily translate into consistent disease control under more realistic growing conditions. Under the conditions evaluated in this project, the biological products could not replace conventional fungicides, particularly under high disease pressure. Potassium phosphite showed the greatest and most consistent potential among the products evaluated and could be considered as a complementary component of an integrated disease management strategy. Low-dose melatonin also deserves further investigation for early blight management.

Further trials over multiple growing seasons and under different environmental conditions are needed to determine the consistency of these products. Future studies should focus on optimising application dose and timing, further evaluating the response to low-dose melatonin, and testing combinations of the most promising biological products with reduced fungicide programmes. This will help determine whether conventional fungicide use can be reduced without compromising disease control.

Background

Potato is one of the world's most important food crops and plays a major role in European agriculture. However, potato production is continuously threatened by several diseases that reduce both yield and tuber quality. Among these, late blight caused by *P. infestans* and early blight caused by *Alternaria* spp. are two of the most economically important foliar diseases. Late blight can spread rapidly under favourable environmental conditions and may destroy entire crops if left uncontrolled. Early blight develops more gradually but causes premature leaf senescence, reduces photosynthetic activity and ultimately decreases tuber yield and quality. Effective management of both diseases is therefore essential for profitable potato production.

Current disease management depends largely on repeated applications of chemical fungicides. In many potato-growing regions, fungicides are applied weekly or several times during a single growing season to maintain adequate protection against late blight. While these programmes have been effective, they increase production costs and have raised concerns regarding environmental and aquatic sustainability, resistance development in pathogen populations and regulatory restrictions on pesticide use. The European Green Deal and the Farm to Fork Strategy aim to reduce the use and risk of chemical pesticides by 50% before 2030. Achieving this target will require the development and validation of alternative crop protection strategies that maintain crop productivity while reducing reliance on conventional fungicides.

Agricultural biological products have received increasing attention as environmentally friendly alternatives to conventional pesticides. These products include microbial inoculants, plant-derived compounds, resistance inducers, biostimulants and naturally occurring molecules that improve plant health or suppress pathogens. Some biological products act directly on plant pathogens, whereas others stimulate the plant's own defence mechanisms or improve overall plant vigour. Because many of these products are biodegradable and generally considered to have lower environmental risks than synthetic fungicides, they are viewed as important components of future sustainable crop production systems.

Despite the increasing commercial availability of biological products, independent evaluations under field conditions remain limited. Many products have demonstrated promising results in laboratory or greenhouse experiments, but disease pressure, environmental variation and interactions with crop management practices often reduce their effectiveness under commercial production conditions. Consequently, there is a need for well-designed field experiments that compare biological products with existing disease management programmes and generate unbiased information for growers and industry.

This project was initiated to address this knowledge gap by evaluating selected biological products under controlled field conditions. The study was carried out at the Aarhus University experimental station in Flakkebjerg, Denmark, where separate experiments were established for late blight and early blight using artificial inoculation. The project combined disease assessments with measurements of yield, tuber quality and starch content to determine whether the treatments influenced crop performance beyond disease suppression. In addition to providing information on the effectiveness of individual biological products, the study aimed to generate practical knowledge that can support the future development of integrated disease management strategies for potato production.

Objectives

The objectives of the project were to evaluate selected biological products for the management of potato late blight and early blight under field conditions and compare their performance with a standard fungicide programme and an untreated control. The project aimed to determine whether these biological products could reduce disease development while maintaining yield and tuber quality. In addition, physiological and quality-related measurements were included to identify possible effects of the treatments beyond disease suppression. The project also sought to generate independent field-based data that can contribute to the development of sustainable crop protection strategies and support the future use of biological products as part of integrated disease management programmes.

Materials and Methods

Controlled-environment evaluation

Greenhouse and in vitro experiments were conducted to evaluate selected treatments against potato early blight caused by *A. solani*. Two potato cultivars, Bintje and Kuras, were treated with two concentrations of melatonin (0.1 and 0.5 mM), two concentrations of the essential-oil-based product NoMo (0.5 and 2%), or potassium phosphite. Plants received four foliar applications at weekly intervals before leaves were inoculated with *A. solani*, after which disease incidence and lesion area

were assessed. In parallel, in vitro assays were conducted to determine the direct effects of different concentrations of NoMo and melatonin on *A. solani* mycelial growth.

Field experiments

Field experiments were conducted during the 2023 growing season at the Aarhus University experimental station in Flakkebjerg, Denmark. The study was designed to evaluate the effectiveness of selected biological products [BABA, NoMold (High and Low concentration), Potassium Phosphite, Standard, Untreated] against potato late blight and [BABA, NoMold (High and Low concentration), Melatonin (High and Low concentration), Potassium Phosphite, Standard, Untreated] early blight under field conditions. To ensure reliable disease development and minimise interference between pathogens, separate experiments were established for late blight and early blight. Artificial inoculation was used in both experiments to provide uniform disease pressure and to allow direct comparison of treatment effects under controlled field conditions.

The experiments were laid out as a randomized complete block design with four replications. Each treatment was randomly assigned within each block to minimise the effects of field variability. Individual plots measured approximately 20 m², providing sufficient plant material for disease assessments, physiological measurements and final harvest evaluations. The potato cultivar 'Bintje', which is highly susceptible to *P. infestans*, was used in the late blight experiment. The cultivar 'Kuras' was used in the early blight experiment because of its suitability for evaluating disease development and tuber quality under field conditions.

The treatments included selected biological products with different modes of action together with appropriate reference treatments. Potassium phosphite was included as a positive reference because previous studies have demonstrated its ability to reduce late blight development and to induce defence responses in potato. A standard fungicide programme representing current commercial practice was included as the disease control standard, while untreated plots served as the negative control. The biological products evaluated in this study included compounds with reported antifungal or plant defence-inducing properties that have shown promising results in laboratory or greenhouse studies.

Artificial inoculation was carried out separately for each disease. The late blight experiment was inoculated with *P. infestans*, whereas the early blight experiment received inoculum of *A. solani*. Controlled inoculation ensured that all treatments were exposed to a similar level of disease pressure and that disease development started at approximately the same time across all plots. Disease assessments were carried out at regular intervals following inoculation. Disease severity was visually estimated by assessing the percentage of infected foliage within each plot, allowing disease progress to be monitored throughout the season.

At crop maturity, each plot was harvested separately to determine total tuber yield. Tubers from individual plots were graded according to weight and quality. Attention was given to tuber rot and common scurf because these parameters can influence the market value of the harvested crop. Tuber grading was performed using standard evaluation procedures, and representative tubers from each treatment were photographed to document treatment effects. Tuber starch content was determined using the underwater weight (specific gravity) method. Approximately 2 kg of tubers from each plot were initially analysed using an industrial specific gravity instrument, and starch content was calculated according to the International Starch Institute method (International starch institute Denmark). The analysis was repeated using a larger sample size of 5 kg to verify the results. The formula used for calculating the tuber starch content is $\text{Specific gravity} \times 215.17 - 218.23$. The collected tubers were also graded and scored for tuber weight, tuber rot and common scurf as part of the tuber quality among individual plots.

Semi-field experiments

Additional semi-field experiments were conducted in 2024 to further evaluate the performance of selected biological products against early and late blight. The early blight experiment was conducted with the potato cultivar Kuras and the late blight experiment with Bintje. Both experiments included five replicates per treatment. Plants were inoculated on 24 July 2024 with a suspension containing 10,000 propagules per ml of *A. solani* for the early blight experiment or *P. infestans* for the late blight experiment.

The treatments included NoMold at 2 and 4 l/ha, BABA at 200 g/ha, potassium phosphite (Proalexin) at 4 l/ha, Lantana acetone extract at 3.75 mg/ml, Lantana ethyl acetate extract at 1.875 mg/ml, orange oil at 0.8%, Moringa extract at 3.75 mg/ml, and melatonin at 0.1 and 0.5 mM. Untreated plants and standard fungicide treatments were included as controls. Narita at 0.4 l/ha was used as the standard treatment in the early blight experiment, while Shirlan Ultra at 0.4 l/ha was used in the late blight experiment. Treatments were applied on 12 and 19 July before inoculation and again on 26 July and 2 August after inoculation. Disease severity was assessed following treatment to compare the level of early and late blight control provided by the different treatments.

All data were analysed using analysis of variance (ANOVA) to determine treatment effects on disease severity, yield, tuber quality and starch content. Where appropriate, treatment means were compared to identify statistically significant differences.

Results

3.1 Controlled-environment evaluation

The controlled-environment experiments demonstrated treatment- and cultivar-dependent effects against *A. solani*. In Bintje, 2% NoMo, 0.5 mM melatonin and potassium phosphite reduced the proportion of infected leaves to approximately 33–38%, compared with 71% in the untreated control, and also reduced mean lesion area. The strongest response was observed with 2% NoMo, for which lesion severity was approximately 12% of the control, followed by 0.5 mM melatonin (18%) and potassium phosphite (55%). In Kuras, treatment effects were less pronounced, although 2% NoMo reduced overall lesion severity to approximately 52% of the control. Kuras generally developed more frequent and larger lesions than Bintje. In vitro assays further demonstrated inhibition of *A. solani* growth by higher concentrations of NoMo (Figure 1).

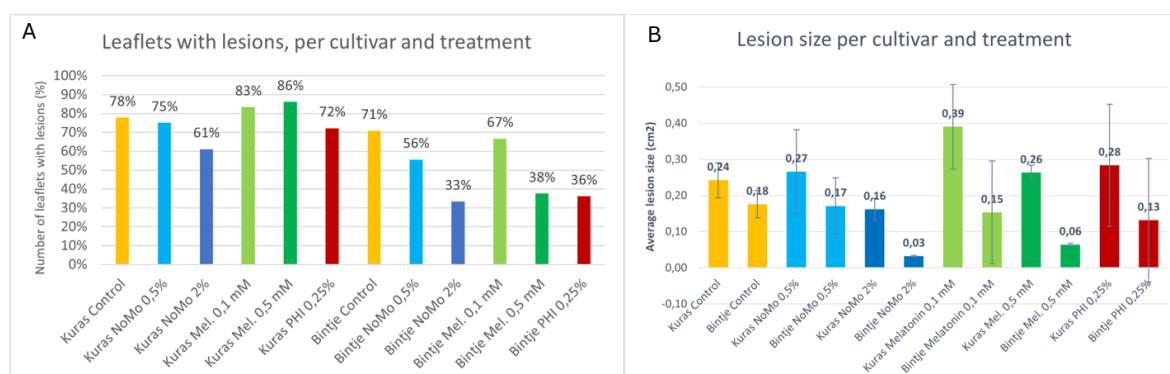


Figure 1. Effect of selected biological treatments on early blight development in potato cultivars Kuras and Bintje under controlled conditions. Percentage of leaflets with lesions (A) and average lesion size (B) following inoculation with *A. solani*. Bars represent treatment means; error bars in the right panel indicate variation among replicates.

3.2 In vitro evaluation of NoMo against *Alternaria solani*

In vitro assays showed that NoMo inhibited the mycelial growth of *A. solani* in a concentration-dependent manner (Figure 2). In the first assay, strong inhibition was observed at the higher NoMo concentrations, with very limited fungal growth at concentrations of 10% and above. A second assay using a narrower concentration range (1–2.5%) confirmed a gradual reduction in mycelial growth with increasing NoMo concentration. These results demonstrate a direct inhibitory effect of NoMo on *A. solani* under in vitro conditions.

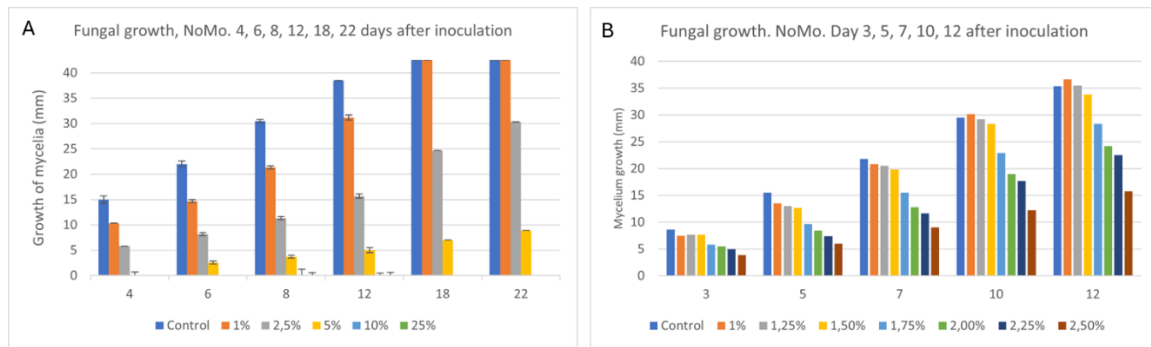


Figure 2. In vitro effect of NoMo concentration on mycelial growth of *Alternaria solani*. Mycelial growth of *A. solani* at different NoMo concentrations measured over time in two independent growth assays. (A) NoMo concentrations of 1–25%; (B) a narrower concentration range of 1–2.5%. Bars represent mean mycelial growth (mm); error bars are shown where available.

3.3 Disease development

Disease development differed considerably among the treatments in both the late blight and early blight experiments. As expected, disease progressed rapidly in the untreated control plots following artificial inoculation, confirming that disease pressure was sufficient to evaluate treatment performance under field conditions (Figure 3).

In the late blight experiment, the standard fungicide programme provided almost complete protection throughout the assessment period and effectively suppressed the development of *P. infestans*. Among the biological treatments, potassium phosphite consistently reduced disease severity compared with the untreated control. Although the level of protection was lower than that obtained with the standard fungicide programme, phosphite was the only biological treatment that showed a clear protective effect throughout the experiment. The remaining biological treatments provided little or inconsistent disease suppression, and disease progression in these treatments was generally comparable to that observed in the untreated control (Figure 3).

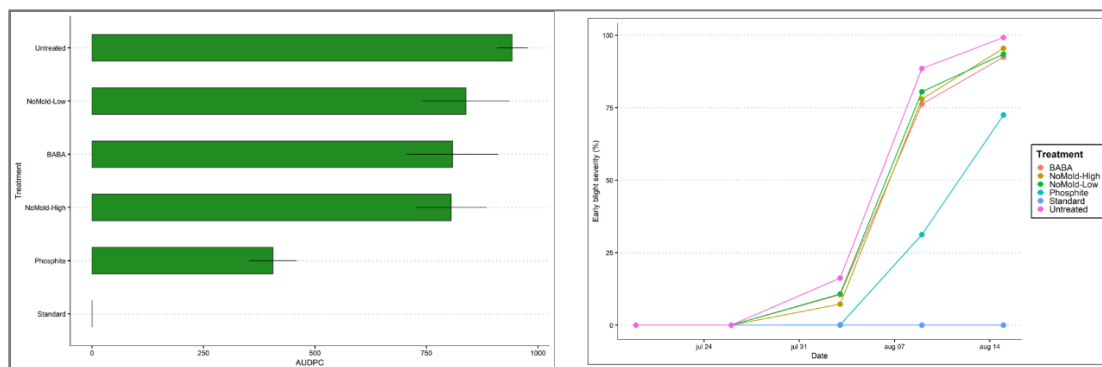


Figure 3. Effect of different treatments on the development of potato late blight under field conditions. Disease development of potato late blight caused by *P. infestans* under different treatment

regimes in the 2023 field experiment conducted at Flakkebjerg, Denmark. The left panel shows the area under the disease progress curve (AUDPC), while the right panel illustrates disease progression over time following artificial inoculation. Treatments included BABA, MoldGuard formulations (high and low concentrations), potassium phosphite, a standard fungicide programme, and an untreated control. Bars represent mean AUDPC values with standard error ($\pm$ SE, $n = 4$). Disease severity is expressed as the percentage of infected foliage. Lower AUDPC values indicate better disease control. The standard fungicide programme provided complete protection throughout the experiment, whereas potassium phosphite was the most effective among the biological treatments.

A similar trend was observed in the early blight experiment. Disease symptoms developed progressively after inoculation with *A. solani*, and the untreated control showed the highest disease severity by the end of the assessment period. The standard fungicide treatment again provided best disease control, with only limited symptom development during the experiment. Potassium phosphite reduced disease severity relative to the untreated control and showed the most consistent effect among the biological treatments. However, the reduction in disease severity was smaller than that achieved by the standard fungicide programme. The other biological products did not provide consistent protection against early blight under the conditions of this study (Figure 4).

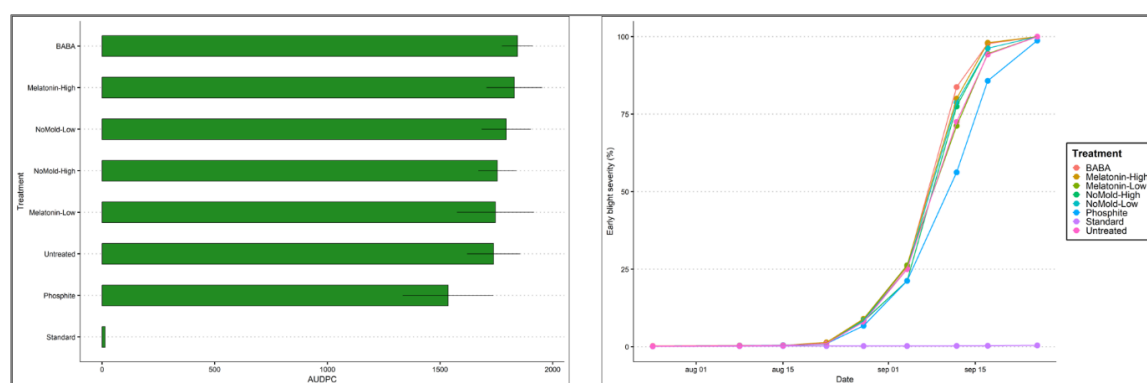


Figure 4. Effect of different treatments on the development of potato early blight under field conditions. Area under the disease progress curve (AUDPC) (left) and disease progression over time (right) for potato early blight caused by *A. solani* under different treatment regimes in the 2023 field experiment at Flakkebjerg, Denmark. Treatments included BABA, melatonin (high and low concentrations), MoldGuard formulations, NoMold (high and low concentrations), potassium phosphite, a standard fungicide programme, and an untreated control. Bars represent the mean AUDPC values, and error bars indicate the standard error of the mean ($n = 4$). Disease severity was assessed periodically after inoculation and expressed as the percentage of infected foliage. Lower AUDPC values indicate better disease control. The standard fungicide programme provided the highest level of protection, while phosphite was the most effective among the biological treatments.

3.4 Tuber yield

Total tuber yield was determined at harvest for all treatments in both experiments. Although differences in disease severity were evident during the growing season, these differences were only partly reflected in final yield. Overall, yield variation among treatments was relatively small, and no substantial yield advantage was observed for most of the biological treatments compared with the untreated control (Figure 5).

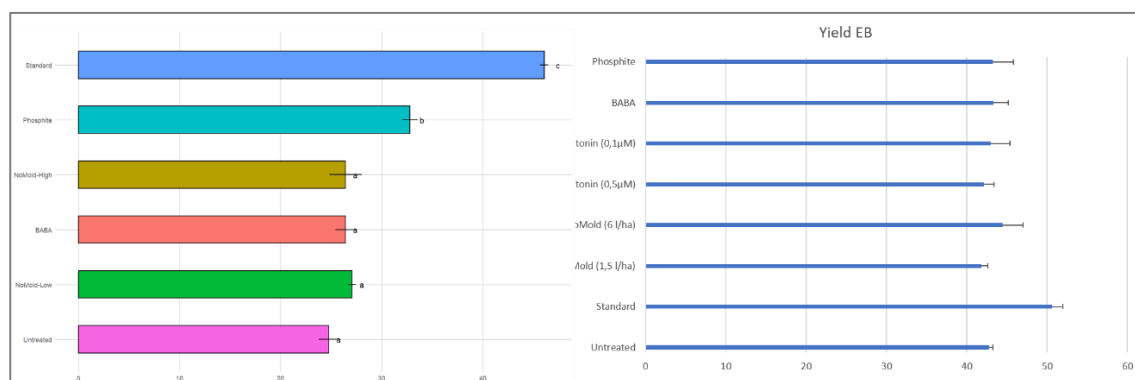


Figure 5. Effect of different treatments on potato tuber yield in the late blight (LB) (left) and early blight (EB) (right) field experiments conducted at Flakkebjerg, Denmark, during the 2023 growing season. Yield was determined at harvest and is presented as the mean $\pm$ standard error (SE) of four replicate plots. Treatments included potassium phosphite, BABA, melatonin (0.1 and 0.5 μ M), MoldGuard formulations (low and high concentrations), a standard fungicide programme, and an untreated control. Different lowercase letters above the bars in the late blight experiment indicate significant differences among treatments according to ANOVA followed by Tukey's multiple comparison test ($P < 0.05$). The standard fungicide treatment produced the highest tuber yield in the late blight experiment, whereas no significant differences in yield were observed among treatments in the early blight experiment.

Plots receiving the standard fungicide programme generally produced the highest yields, which was expected because disease development was effectively controlled throughout the season. Potassium phosphite also maintained yields comparable to the standard treatment, reflecting its partial suppression of disease development. The remaining biological treatments produced yields that were generally similar to those of the untreated control, indicating that their level of disease suppression was insufficient to generate measurable improvements in productivity under the conditions of this experiment (Figure 5). The relatively small differences in yield suggest that factors other than foliar disease severity may also have influenced final production. Environmental conditions during tuber development, together with natural variation between experimental plots, may have contributed to the relatively limited treatment effects observed at harvest.

3.5 Tuber quality

Tuber quality was evaluated after harvest using standard grading procedures. The assessment included tuber weight, tuber rot and common scurf, as these parameters directly influence market quality and economic value. Analysis of variance showed that tuber weight was the only parameter significantly affected by treatment. The remaining quality parameters, including tuber rot and common scurf, did not differ significantly among treatments. Although symptoms of tuber rot and common scurf were observed in several plots, considerable variation existed between replicates, making it difficult to detect statistically significant treatment effects (Table 1).

The large variability observed among field plots suggested that local field conditions may have influenced disease development and tuber quality. Consequently, the observed differences in tuber rot and common scurf could not be confidently attributed to the treatments alone. During data evaluation, the possibility of incorporating spatial variation into the statistical analysis was considered to improve the interpretation of these parameters. However, this was beyond the scope of the present report.

Representative photographs taken during tuber grading supported the quantitative observations and illustrated the variation in tuber appearance among treatments (Figure 6). However, no obvious visual differences were observed between most biological treatments and the untreated control.

Table 1. Tuber quality parameters measured following different treatments in the late blight field experiment.

Serial No.	Plot number	Treatment	Average Size(cm)	Average Width (cm)	Average Weight of tuber (gm)	% of tuber rot	% of Black scurf
1	101	Untreated	8.782	4.806	124.629	52	38
2	203	Untreated	8.562	5.268	116.848	82	26
3	303	Untreated	7.966	5.008	98.94	48	30
4	402	Untreated	7.375	4.516	80.855	47	26
5	102	Standard	8.874	5.038	124.547	56	14
6	201	Standard	9.715	5.501	135.629	31.5	62.1
7	302	Standard	8.034	4.934	111.649	37	35
8	404	Standard	8.785	5.39	135.451	55	50
9	103	NoMold (1,5 kg/ha)	8.926	4.894	116.464	56	82
10	205	NoMold (1,5 kg/ha)	7.702	5.062	89.53	54	90
11	304	NoMold (1,5 kg/ha)	7.766	4.617	93.794	50	45
12	401	NoMold (1,5 l/ha)	7.408	4.651	77.593	65	75
13	104	NoMold (6 lg/ha)	7.68	4.67	98.97	60	68
14	206	NoMold (6 lg/ha)	7.58	4.572	88.542	34	45
15	301	NoMold (6 lg/ha)	8.172	4.256	95.046	40	36
16	405	NoMold (6 lg/ha)	7.66	5.274	89.231	58	4
17	105	BABA	7.735	5.37	93.803	69	76
18	204	BABA	8.634	4.834	107.07	60	64
19	305	BABA	7.268	4.682	85.385	16	24
20	406	BABA	7.334	4.238	80.104	32	22
21	106	Phosphite	9.128	4.868	122.138	60	51
22	202	Phosphite	8.147	4.661	102.874	74	85
23	306	Phosphite	8.662	5.73	128.36	50	11
24	403	Phosphite	8.206	5.136	122.047	10	36



Figure 6. Representative tubers from the untreated control (Plot - 101) showing external and internal symptoms following the late blight field experiment.

3.6 Starch content

Tuber starch content was determined using the specific gravity method to evaluate whether the treatments influenced tuber quality beyond disease suppression. Initial measurements were carried out using approximately 2 kg of tubers collected from each plot and starch content was calculated according to the International Starch Institute method.

The measured starch content in Kuras (Table 2) and Bintje (Table 3) were consistently lower than expected across all treatments. To confirm that these results were not due to sampling error, the measurements were repeated using a larger sample size of approximately 5 kg of tubers per treatment (Date not shown). The repeated analysis produced similar results, confirming that starch content remained low irrespective of sampling weight. No consistent treatment effects on starch content were observed, and differences among treatments were small.

The absence of treatment effects indicates that none of the biological products substantially influenced starch accumulation under the conditions of this study. Instead, the low starch values observed across all treatments suggest that environmental conditions, cultivar characteristics or seasonal growing conditions may have had a greater influence on starch accumulation than disease management treatments.

Table 2. Starch content and specific gravity of Kuras cv. potato tubers following different treatments in the late blight field experiment.

Sno.	Plot number	Treatment	Dry Matter	Specific gravity	Dry weight	Wet Weight	Dry Basket	Wet Basket	Starch
1	101	Untreated	13.17	1.047	2597	714	586	526	7.05
2	204	Untreated	16.8	1.064	2520	734	586	526	10.71
3	307	Untreated	16.74	1.064	2733	756	586	526	10.71
4	404	Untreated	16.8	1.064	2614	744	586	526	10.71
5	102	Standard	19.08	1.075	2573	755	586	526	13.08
6	208	Standard	19.06	1.075	2600	758	586	526	13.08
7	301	Standard	18.04	1.07	2552	745	586	526	12
8	405	Standard	18.09	1.07	2652	758	586	526	12
9	103	MoMold (1,5 l/ha)	18.55	1.072	2558	751	586	526	12.43
10	201	MoMold (1,5 l/ha)	17.05	1.065	2634	748	586	526	10.93
11	305	MoMold (1,5 l/ha)	15.49	1.058	2616	734	586	526	9.42
12	407	MoMold (1,5 l/ha)	16.65	1.063	2616	734	586	526	10.5
13	104	NoMold (6 l/ha)	16.48	1.062	2557	734	586	526	10.28
14	207	NoMold (6 l/ha)	17.71	1.068	2633	753	586	526	11.57
15	304	NoMold (6 l/ha)	17.24	1.066	2699	755	586	526	11.14
16	401	NoMold (6 l/ha)	17.12	1.065	2630	748	586	526	10.93
17	105	latonin (0,5µM)	16.25	1.061	2573	7343	586	526	10.07
18	206	latonin (0,5µM)	15.87	1.059	2591	733	586	526	9.64
19	306	latonin (0,5µM)	16.02	1.06	2576	734	586	526	9.85
20	406	latonin (0,5µM)	17.28	1.066	2514	737	586	526	11.14
21	106	latonin (0,1µM)	15.03	1.055	2566	724	586	526	8.8
22	202	latonin (0,1µM)	15.36	1.057	2629	733	586	526	9.2
23	302	latonin (0,1µM)	16.46	1.062	2605	739	586	526	10.3
24	408	latonin (0,1µM)	16.48	1.062	2566	735	586	526	10.3
25	107	BABA	16.19	1.061	2558	732	586	526	10.1
26	203	BABA	16.67	1.063	2605	742	586	526	10.5
27	308	BABA	16.95	1.065	2641	748	586	526	10.9
28	402	BABA	15.68	1.059	2660	740	586	526	9.6
29	108	Phosphite	17.5	1.067	2588	745	586	526	11.4
30	205	Phosphite	16.38	1.062	2554	733	586	526	10.3
31	303	Phosphite	16.8	1.064	2600	741	586	526	10.7
32	403	Phosphite	17.03	1.065	2673	752	586	526	10.9

Table 3. Starch content and specific gravity of Bintje cv. potato tubers following different treatments in the late blight field experiment.

Sno.	Plot numb	Treatment	Dry Matter	Specific gravity	Dry weight	Wet Weight	Dry Basket	Wet Basket	Starch
1	101	Untreated	10.64	1.1516	2119	279	125	116	11.445
2	203	Untreated	8.06	1.1382	2117	257	125	116	8.529
3	303	Untreated	8.95	1.1429	2128	266	125	116	9.544
4	402	Untreated	9.77	1.1456	2124	270	125	116	10.145
5	102	Standard	9.05	1.1429	2128	266	125	116	9.544
6	201	Standard	8.46	1.1405	2127	262	125	116	9.030
7	302	Standard	9.96	1.1478	2112	272	125	116	10.621
8	404	Standard	11.12	1.1429	2519	315	125	116	9.558
9	103	NoMold (1,5 l/ha)	8.44	1.1402	2115	260	125	116	8.960
10	304	NoMold (1,5 l/ha)	8.63	1.1398	2128	261	125	116	8.881
11	401	NoMold (1,5 l/ha)	10.36	1.1460	2214	282	125	116	10.217
12	104	NoMold (6 l/ha)	7.77	1.1371	2107	254	125	116	8.292
13	206	NoMold (6 l/ha)	8.97	1.1414	2131	264	125	116	9.229
14	301	NoMold (6 l/ha)	8.23	1.1393	2110	258	125	116	8.776
15	405	NoMold (6 l/ha)	8.17	1.1391	2104	257	125	116	8.740
16	105	BABA	9.6	1.1445	2130	269	125	116	9.910
17	204	BABA	9.3	1.1442	2126	268	125	116	9.844
18	305	BABA	8.23	1.1377	2131	258	125	116	8.437
19	406	BABA	8.69	1.1400	2134	262	125	116	8.916
20	106	Phosphite	9.64	1.1460	2119	270	125	116	10.231
21	202	Phosphite	9.03	1.1431	2117	265	125	116	9.594
22	306	Phosphite	9.14	1.1431	2133	267	125	116	9.594
23	403	Phosphite	9.24	1.1443	2109	266	125	116	9.863

Semi-field evaluation

The 2024 semi-field experiments provided further information on the performance of the biological treatments against early and late blight. Seven days after the final treatment, clear differences in disease severity were observed among treatments, although none of the alternative treatments provided the same level of disease control as the standard fungicides.

In the late blight experiment with Bintje, the standard fungicide treatment showed the lowest disease severity. Among the alternative treatments, potassium phosphite provided the best disease suppression, with late blight severity of approximately 25% (Figure 7). In comparison, disease severity exceeded 50% for most of the other alternative treatments. This confirmed the comparatively stronger activity of phosphite against late blight observed in the other field experiment.

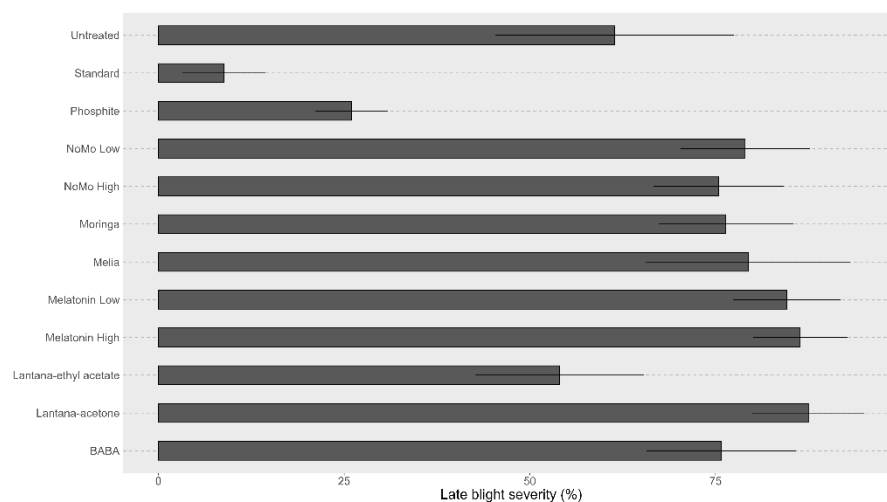


Figure 7. Effect of biological treatments on late blight severity in potato under semi-field conditions. Late blight severity (%) in Bintje following inoculation with *P. infestans*. Treatments were compared with untreated control and a standard fungicide treatment. Bars represent mean disease severity, and error bars indicate variation among five replicates.

In the early blight experiment with Kuras, the standard fungicide treatment again provided the strongest disease control. Among the alternative treatments, low-concentration melatonin (0.1 mM) showed the lowest early blight severity. Phosphite, NoMold and some of the other treatments showed intermediate or limited effects, but none provided disease control comparable to the standard fungicide treatment (Figure 8).

NoMold did not significantly reduce disease severity compared with the untreated control in either experiment. In the late blight experiment, both NoMold treatments showed numerically higher disease severity than the untreated plants. In the early blight experiment, disease severity following NoMold treatment was similar to or higher than the untreated control, with a tendency towards greater disease severity at the higher application rate of 4 l/ha. Overall, only the standard fungicide treatments resulted in significantly lower disease severity than the untreated control for both early and late blight (Figure 9).

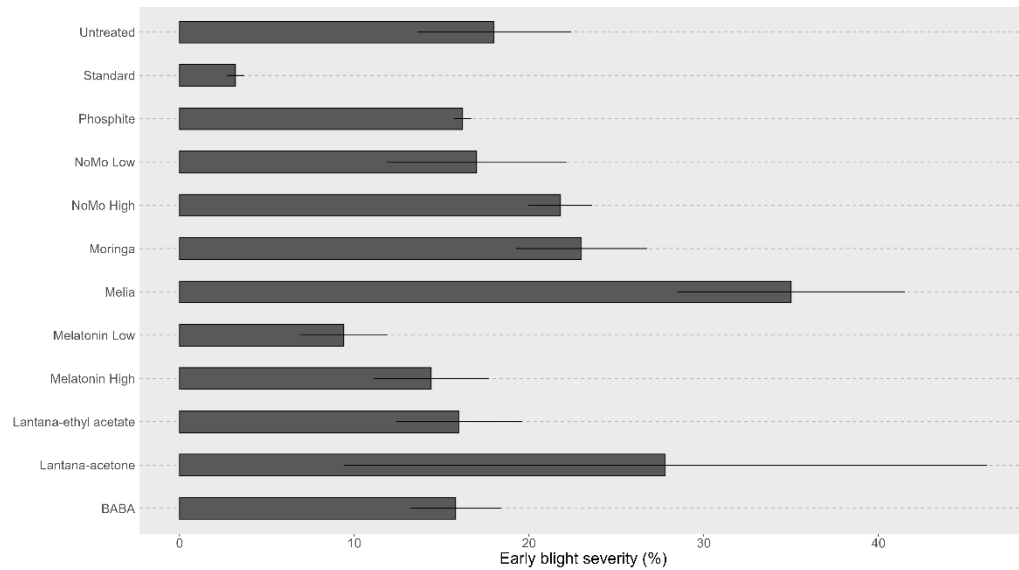


Figure 8. Effect of biological treatments on early blight severity in potato under semi-field conditions. Early blight severity (%) in Kuras following inoculation with *A. solani*. Treatments were compared with an untreated control and a standard fungicide treatment. Bars represent mean disease severity, and error bars indicate variation among five replicates.

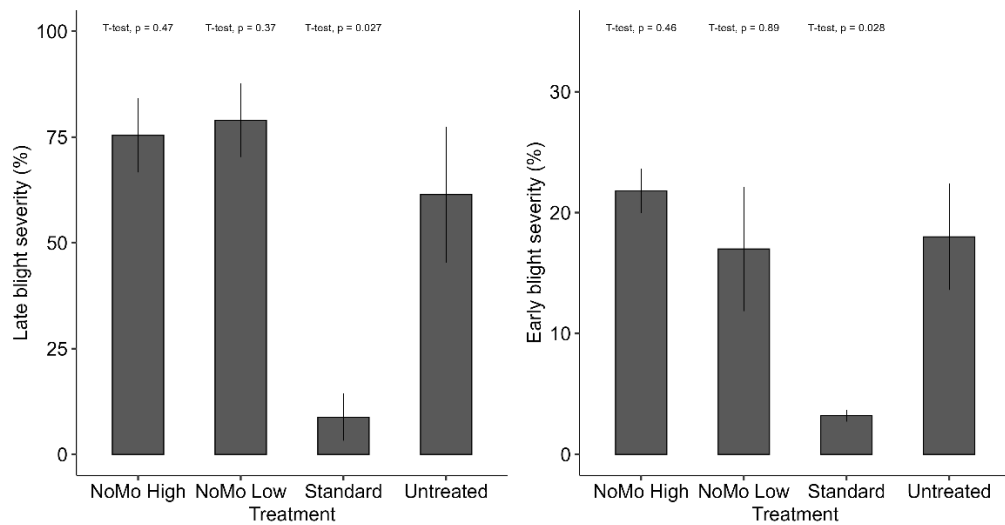


Figure 9. Comparison of NoMold and standard fungicide treatments for late (left) and early blight (right) severity under semi-field conditions. NoMold at high (4 L/ha) and low (2 L/ha) rates, standard fungicide treatment, and untreated control. Bars represent mean disease severity $\pm$ variation among five replicates. P-values from pairwise t-tests against the untreated control are shown above the respective treatments.

Discussion

The main objective of this project was to evaluate the performance of selected biological products against potato late blight and early blight under controlled, semi-field and field conditions, with particular emphasis on their performance under more realistic growing conditions. Although many biological products have shown promising activity under laboratory and greenhouse conditions, their performance under field conditions is often more variable because disease development and treatment efficacy are influenced by environmental conditions, pathogen pressure, crop growth stage and

application timing. Therefore, field validation is an essential step before biological products can be recommended for commercial use (Bardin et al., 2015; Pertot et al., 2017; Liljeroth et al., 2025; Pöldmets et al., 2025).

Across the field and semi-field experiments, clear differences were observed among treatments. As expected, the standard fungicide programme consistently provided the highest level of disease control against both late blight and early blight. This was also evident in the 2024 semi-field experiments, where the standard treatments resulted in the lowest disease severity for both diseases. In the specific comparison between NoMold, the standard treatment and the untreated control, only the standard treatment resulted in significantly lower disease severity than the untreated control. These results confirm that conventional fungicides remain the most reliable option for disease management under high disease pressure. Similar observations have been reported in previous field studies, where repeated fungicide applications consistently provided better disease suppression than most biological alternatives (Cooke et al., 2011; Savary et al., 2019; Liljeroth et al., 2025).

Among the biological treatments, potassium phosphite showed the most consistent reduction in disease development, particularly against late blight. Although the level of protection was lower than that obtained with the standard fungicide programme, phosphite reduced disease development across the experiments. This response was again evident in the 2024 semi-field late blight experiment, where phosphite was the best-performing alternative treatment, with disease severity of approximately 25%, compared with more than 50% for most of the other alternative treatments. The protective effect of potassium phosphite has been reported previously in potato and several other crops, where it can act both through direct effects on oomycetes and by stimulating plant defence responses (Lobato et al., 2011; Liljeroth et al., 2016). The repeated response observed in the present project therefore strengthens the evidence that phosphite is one of the more promising treatments evaluated and may have potential as part of an integrated disease management strategy. However, its level of protection remained below that obtained with the standard fungicide treatments.

The 2024 experiment also provided an interesting result for melatonin against early blight. Among the alternative treatments, the low concentration of melatonin (0.1 mM) resulted in the lowest early blight severity, whereas the higher concentration showed less disease suppression. This suggests that the response to melatonin may depend on treatment concentration and that a higher dose does not necessarily result in improved disease control. Melatonin has been reported to influence plant defence through regulation of oxidative balance, defence signalling and interactions with other plant hormones, and direct effects against plant pathogens have also been reported (Zhang et al., 2017; Gupta, 2023). However, responses can vary depending on experimental conditions. A recent study in potato found that exogenous melatonin did not increase resistance to *A. solani* or *P. infestans* in detached-leaf assays (Jones, 2025). The present results therefore indicate that low-dose melatonin deserves further investigation against potato early blight, particularly with regard to application concentration, timing and environmental conditions.

In contrast, the remaining biological products generally showed limited or inconsistent effects under semi-field and field conditions. The 2024 experiments expanded the range of alternatives evaluated to include Moringa extract, Lantana extracts and orange oil in addition to NoMold, BABA, phosphite and melatonin. None of these additional treatments provided disease control comparable to the standard fungicide treatments. This does not necessarily indicate that these products lack biological activity. Biological products can be strongly influenced by environmental conditions, formulation, application timing, product concentration and disease pressure, and their performance may therefore vary between experimental systems, locations and growing seasons (Bardin et al., 2015; Köhl et al., 2019). The results of the project demonstrate the importance of evaluating promising products over multiple experiments before conclusions are made regarding their practical potential.

The controlled-environment and in vitro experiments conducted within the project provide particularly useful information for interpreting these results. Under controlled conditions, treatment effects against *A. solani* were more evident and differed between the two potato cultivars. In Bintje, NoMo, melatonin

and potassium phosphite reduced disease development, whereas the effects were less pronounced in Kuras. The in vitro experiments also showed that NoMo directly inhibited the mycelial growth of *A. solani*, with stronger inhibition at higher concentrations. Similar direct inhibitory effects of essential-oil-based treatments against *A. solani* have previously been reported (El-Mougy, 2009). However, the promising activity of NoMo under controlled conditions was not reproduced under the 2024 semi-field conditions. Neither the low nor high NoMold treatment significantly improved disease control compared with the untreated treatment. In the late blight experiment, both NoMold treatments showed numerically higher disease severity than the untreated control, while in the early blight experiment disease severity was similar to or higher than the untreated control. There was also a tendency towards greater early blight severity at the higher NoMold application rate.

The contrasting response of NoMold across the experimental systems is an important finding of the project. Strong inhibition of pathogen growth in vitro does not necessarily mean that a product will provide effective disease control when applied to plants. Product formulation, stability on the leaf surface, environmental conditions, application rate, cultivar and interactions with plant physiology may all influence treatment efficacy. Furthermore, the 2024 results suggest that simply increasing the NoMold application rate did not improve disease control. The present data are not sufficient to determine why this occurred, and therefore it would be premature to conclude that the product negatively affected the plants. Instead, these results highlight the need to optimise formulation, concentration and application strategy and to validate laboratory findings under increasingly realistic experimental conditions. Differences between controlled-environment and field performance are recognised as an important challenge in the development of biological crop protection products (Köhl et al., 2019; Lankinen et al., 2024).

Despite clear differences in foliar disease development, only relatively small differences in yield were observed among treatments in the field experiment where yield was assessed. This finding was somewhat unexpected, as improved disease control would generally be expected to result in higher tuber production. However, tuber yield in potato is determined by several interacting factors, including environmental conditions, the timing and duration of disease pressure, cultivar characteristics, canopy development and the physiological status of the crop. Consequently, disease severity alone does not always translate directly into yield loss, particularly when disease develops after the major tuber bulking period or when favourable growing conditions compensate for foliar damage (Struik, 2010; Dong & Zhou, 2022).

It is therefore possible that disease developed relatively late in the growing season, after a substantial proportion of tuber growth had already occurred, thereby reducing its effect on final yield. Similar observations have been reported in studies showing that the timing of late blight epidemics can be important in determining yield loss (Nærstad et al., 2007; Cooke et al., 2011). In addition, experimental variability among replicate plots may have reduced the statistical power to detect relatively small treatment differences. Field experiments evaluating disease management can exhibit considerable spatial variation due to differences in soil properties, crop establishment and microclimatic conditions, making small treatment effects more difficult to detect statistically.

The evaluation of tuber quality produced similar observations. Among the parameters assessed, only tuber weight differed significantly among treatments, whereas tuber rot and **black scurf** showed no statistically significant differences. Considerable variation was observed among replicate plots for these quality parameters. Field experiments naturally include spatial variability arising from differences in soil properties, moisture conditions and microclimate, all of which may influence disease development and tuber quality (Siano et al., 2024). Although the randomized block design reduces some of this variation, residual spatial variability may remain and can reduce the ability to detect treatment effects. More advanced statistical approaches incorporating spatial correction could improve the precision of future analyses, particularly when disease incidence is relatively low or unevenly distributed across the experimental field (van Es et al., 2007).

Starch content was consistently low irrespective of treatment. Repeating the analysis using larger tuber samples produced similar values, indicating that the observed results were not caused by sampling error. The lack of treatment effects suggests that none of the biological products substantially influenced starch accumulation during the growing season. Instead, starch content was likely influenced more strongly by environmental conditions, seasonal weather, crop maturity and cultivar characteristics than by the disease management treatments themselves. Previous studies have shown that tuber dry matter and starch accumulation are primarily determined by genotype and environmental conditions, while crop protection practices generally influence starch content only indirectly by maintaining a healthy photosynthetic canopy during tuber bulking (Storey, 2007; Siano et al., 2024).

One important outcome of this project is that it highlights the importance of independent evaluation of biological products across different experimental conditions before their adoption by growers. Commercial interest in biological crop protection products has increased rapidly during the past decade as agriculture moves towards more sustainable production systems. However, independent field evaluations remain limited for many products, and their performance under field conditions is often more variable than that observed in laboratory or greenhouse studies due to differences in environmental conditions, disease pressure and crop management practices (Lankinen et al., 2024; Galli et al., 2024). By combining in vitro, controlled-environment, semi-field and field experiments, the present project provides information on how treatment performance can change as products are evaluated under increasingly realistic growing conditions.

The project also demonstrated the importance of evaluating biological products using multiple response variables rather than disease assessments alone. While reducing disease severity remains the primary objective, successful disease management should also maintain crop productivity and tuber quality. In the field experiment, measurements of tuber yield, tuber quality and starch content complemented the disease assessments and provided a more comprehensive evaluation of treatment performance. Such integrated assessments are important for determining the practical value of biological products, as improvements in disease control do not necessarily translate into increased yield or improved tuber quality under field conditions (Dong & Zhou, 2022; Põldmets et al., 2025).

Overall, the combined results show that some biological products have potential to contribute to more sustainable potato disease management, but their efficacy remains less consistent than that of standard fungicide programmes. Potassium phosphite showed the most consistent performance across the experiments, particularly against late blight, and therefore appears to be the strongest candidate for further evaluation within integrated disease management programmes. Low-dose melatonin also showed promising activity against early blight in the 2024 semi-field experiment and deserves further investigation. In contrast, the promising in vitro and controlled-environment activity of NoMo was not reproduced under semi-field conditions, demonstrating the importance of field validation. Future work should therefore focus on optimising dose and timing, evaluating combinations with reduced fungicide programmes, and validating the most promising treatments over multiple growing seasons and under different environmental conditions.

Conclusions

The present project evaluated selected biological products for the management of potato late blight and early blight using in vitro, controlled-environment, semi-field and field experiments. Under controlled conditions, several treatments reduced early blight development, with responses differing between Bintje and Kuras. NoMo also showed direct inhibitory activity against *A. solani* in vitro. However, these promising effects were less consistent under semi-field and field conditions under the disease pressure and environmental conditions present, demonstrating that activity observed under controlled conditions does not necessarily translate into effective disease control under more realistic growing conditions.

Across the experiments, the standard fungicide treatments provided the highest and most consistent level of disease control. Among the biological treatments, potassium phosphite showed the most

consistent performance, particularly against late blight, and was again the best-performing alternative treatment in the 2024 semi-field late blight experiment. Low-dose melatonin (0.1 mM) also showed promising activity against early blight in the 2024 experiment, although this response was not consistent across all experiments and requires further validation. In contrast, the inhibitory effect of NoMo observed under controlled conditions was not reproduced under semi-field conditions.

Although disease severity differed among treatments, the effects on tuber yield, tuber quality and starch content in the field experiment were relatively small. Overall, the results demonstrate the importance of evaluating biological crop protection products across different experimental conditions and over multiple growing seasons. Among the products evaluated, potassium phosphite showed the greatest potential as a component of integrated potato disease management. Further work should focus on optimising application dose and timing, investigating the promising response to low-dose melatonin, evaluating combinations with reduced fungicide programmes, and validating the most promising treatments under different environmental conditions.

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Student thesis within the project

Part of the experimental work in this project was carried out as a bachelor's thesis by Jenny Tyllström at the Swedish University of Agricultural Sciences (SLU). The thesis included controlled-environment and in vitro experiments evaluating selected biological treatments against potato early blight caused by *A. solani*. These experiments complemented the field trials and contributed additional information on treatment efficacy under controlled conditions and the direct inhibitory effect of selected products on the pathogen.

Thesis title: Tyllström, J. (2023). *Biological Control Agents Against Potato Early Blight: Effects on Disease Progression and Plant Health*. Master's thesis, Swedish University of Agricultural Sciences (SLU).

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