Early Blight in Potato: Decade-Long Field Studies Show High Variation in Yield Losses

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Abstract

The actual yield losses due to early blight disease in potato worldwide are not well described, and therefore, we analysed a decade-long series of field trials performed in Sweden. The series involved 18 trials with starch potato and six ware potato trials where early blight infection rate and yield were studied in untreated and fungicide-treated plots. Yield loss was estimated as the difference between the best fungicide strategy with respect to infection rate and untreated. The potential yield loss was calculated from the relationship between infection rate and yield. Yield and yield loss due to early blight were analysed in relation to weather and soil type. In starch potato, the variation in starch yield increase of fungicide-treated potato ranged from 1.9 to 29.9%, with an average of 11.9%. The calculated potential starch yield loss due to early blight was higher, 14.3% on average, reflecting minor infections in fungicide-treated plots. The large range of variation among trials indicates complex interactions among factors influencing infection rate and yield. We did not find any yield loss due to early blight in the ware potato trials. We found positive correlations between average season air temperature and infection rate in untreated plots. There was a negative correlation between average season air temperature and starch yield in both untreated and fungicide-treated plots. We also found a negative relationship between high soil sand content and infection rate. The yield increase due to fungicide treatment was higher on soils with high sand content. The calculated yield increase needed to compensate for the cost of early blight fungicide product sprayed in starch potato was approximately 250 kg starch per ha, corresponding to an approximately 2.7% yield increase. However, it is generally not economically feasible in Sweden to use fungicides against early blight in ware potato ready for harvest before the end of August.

Keywords Early blight · Yield loss · Potato · Climate factors · Soil sand content

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Abbreviations

rAUDPC	Relative area under disease progress curve
rAUC	Relative area under the defoliation curve
RH	Relative humidity
DAP	Days after planting
REAS	The Rural Economy and Agriculture Societies

Introduction

Early blight, caused by the pathogenic fungus *Alternaria solani*, can cause severe damage to the potato crop worldwide. Starch potato has a longer growth period than ware potato. Starch potato is usually grown until the end of September in Sweden, while most winter ware potato cultivars are ready for harvest in the second half of August. Severe infections of early blight seldom start before mid-August in Sweden, and therefore, the disease is mainly a problem in starch potato. To avoid yield losses, fungicides are normally applied four times starting at the beginning of July at 2-week intervals. However, the development of fungicide resistance has reduced the efficacy of active ingredients like azoxystrobin and boscalid (Edin et al. 2019; Odilbekov et al. 2019; Mostafanezhad et al. 2021). New active substances with good efficacy, like fluopyram and mefentrifluconazole, have been registered in potato during recent years, but they possess a risk for new development of fungicide resistance when frequently used. Presently, there are no biocontrol agents available with sufficient effect to be used in practice (Stridh et al. 2022). Several factors like weather, field-specific factors (e.g., soil type), management (e.g., fertilisation), cultivar maturity (early or late) and cultivar resistance have been shown to influence the risk of early blight disease (Stridh et al. 2023). These are important factors to consider when designing economically feasible fungicide application strategies that also avoid or delay the development of fungicide resistance and minimize environmental impact.

The actual yield losses due to early blight disease in potato are not well documented globally, including Sweden. Leiminger and Hausladen (2012) refer to yield loss data from the USA and South Africa, which reported up to 50%. Data from their own multiple-year trials in Germany indicated a range of yield increases subjected to fungicide treatments of 10–30% among trials. Early studies reported a range of yield loss between 5 and 50% (Neergard, 1945). Rotem (1994) discussed the often-occurring discrepancy between damage to foliage and yield loss, which could be caused by the rapid spread of the disease at the end of the season when most of the yield has already been produced. Shtienberg et al. (1990) developed a model for yield loss assessment for potato early blight and late blight (*Phytophthora infestans*). Crop loss was described as a function of disease severity expressed as rAUDPC (relative area under disease progress curve) multiplied by the effect of disease on bulking rate. In Denmark, multiple field trials were conducted between 2015 and 2021 using different potato cultivars to improve the TOMCAST model for early blight management (Abuley and Nielsen 2017; 2019; Abuley et al. 2023). Yellareddygari et al. (2018) performed a meta-analysis of 23 field trials in the midwestern USA and

reported larger yield effects of infections during early stages, tuber initiation to early bulking, compared to infections during late bulking/tuber maturation.

The aim of this study is to quantify and analyse the variation in potato starch yield losses caused by early blight (*Alternaria solani*) over a 10-year period (2014–2023) in Sweden, using extensive field trial data. The study evaluates how different fungicide treatments influence yield outcomes and examines the role of environmental conditions, such as canopy air temperature and relative humidity, in shaping disease pressure and treatment efficacy. In total, 18 trials performed on typical starch potato farmland in southeast Sweden were included in the analysis. Each trial included untreated and 10–14 different treatments, including different fungicides and doses, biocontrol agents, cultivars, and resistance inducers. Data from subsets of these trials have been published before with focus on fungicide resistance (Edin et al. 2019; Odilbekov et al. 2019; Mostafanezhad et al. 2021), effects of biocontrol agents and resistance inducers (Stridh et al. 2022), potassium fertiliser (Stridh et al. 2023) and interactions between early blight and late blight (Brouwer et al. 2020). In this study, data from untreated plots and those treated with the most effective fungicides were used to assess the range of yield losses, trends over time, and correlations with weather conditions and fungicide efficacy. Yield loss was calculated by comparing untreated plots with the best fungicide treatments. The potential yield losses in the absence of disease were calculated by analysing the relationship between severity of infection and yield within each trial. Further, the economic feasibility of fungicide treatment was evaluated by determining the threshold of infection-related yield loss required for cost-effective disease management. While the primary focus was on starch potato, results from six trials involving ware potato were also reported for comparison.

Materials and Methods

Starch Potato Trials

Series of early blight field trials were carried out between 2014 and 2023 at different locations near Kristianstad, Sweden (Table 1). The practical management of the trials was performed by the Rural Economy and Agriculture Societies (REAS, Kristianstad, Sweden). The planting and emergence dates of the field trials are provided in Supplementary Table 1. In all, results from 18 trials where the best fungicide treatment of each trial was compared with untreated control are reported in this study to get an overview of the yield benefits of using fungicides against early blight (Tables 1 and 2). All trials were designed as completely randomised blocks, with each plot being 18 m^2 and arranged in four replicated blocks. Each plot consisted of five rows of plants, with a row spacing of 75 cm and a planting distance of 38 cm between the seed tubers. Only the three middle rows in each plot were evaluated for yield and disease severity. In most of the trials, cultivar (cv.) Kuras was used, although in 2014, cv. Kardal was also included, and in 2016, cv. Stayer was used in two trials.

Table 1 Early blight field trials from 2014 to 2023 at different locations at Kristianstad, Sweden, and the different fungicide treatments and their efficacy by year

Year	Cultivar	Location	Early blight fungicides treatments *	Efficacy (%)
2014	Kuras	Nymö	RevusTop (T1, T2) + Signum (T3, T5, T7, T9)	60 ± 8.2
2014	Kardal	Nymö	RevusTop (T1, T2) + Signum (T3, T5, T7, T9)	59 ± 6.6
2016	Kuras	Nymö	RevusTop (T4, T8, T12); Signum (T6, T10)	64 ± 6.5
2016	Stayer	Nymö	RevusTop (T4, T8, T12); Signum (T6, T10)	52 ± 14.5
2016	Kuras	Helge	RevusTop (T4, T8, T12); Signum (T6, T10)	54 ± 14.9
2016	Stayer	Helge	RevusTop (T4, T8, T12); Signum (T6, T10)	64 ± 14.5
2017	Kuras	Nymö	RevusTop (T4, T8, T12); Signum (T6, T10)	61 ± 4.0
2017	Kuras	Helge	RevusTop (T4, T8, T12); Signum (T6, T10)	82 ± 10.9
2018	Kuras	Nymö	Narita (T3, T7); Propulse (T5, T9)	76 ± 2.1
2018	Kuras	Helge	Narita (T3, T7); Propulse (T5, T9)	88 ± 6.7
2019	Kuras	Nymö	Narita (T3, T7); Propulse (T5, T9)	75 ± 3.4
2019	Kuras	Helge	Narita (T3, T7); Propulse (T5, T9)	96 ± 1.5
2020	Kuras	Nymö	Propulse (T4, T8); Revyona (T6, T10)	97 ± 1.0
2020	Kuras	Helge	Narita (T4, T8); Propulse (T6, T10)	91 ± 6.7
2021	Kuras	Nymö	Propulse (T4, T8); Revyona (T6, T10)	98 ± 1.9
2021	Kuras	Gärds Köpinge	Propulse (T4, T8); Revyona (T6, T10)	94 ± 4.5
2022	Kuras	Åsums boställe	Narita (T4); Propulse (T8), Revyona (T6, T10)	98 ± 1.5
2023	Kuras	Hovby	Revyona (T3, T5, T7, T9)	99 ± 0.8

*T1 (treatment time 1) is the start of late blight fungicide treatments around June 25. Thereafter, weekly treatments T1–T12. Efficacy ± SD is provided. The fungicide active ingredients and dose rates are provided in brackets: Revus Top (Difenoconazole + Mandipropamid; 0.6 L/ha), Signum (Boscalid + Pyraclostrobin; 0.25 kg/ha), Narita (Difenoconazole; 0.4 L/ha, Propulse (Fluopyram + Prothioconazole; 0.45 L/ha), and Revyona (Mefentrifluconazole; 1.25 L/ha)

Ware Potato Trials

Field trials with ware potato were conducted in southern Sweden in 2015 and 2017. The cultivars (cvs.) Bintje and Folva were used. In 2015, the trial was carried out at Helgegården and Nymö, and in 2017, only at Nymö. These trials were also managed by REAS, Kristianstad, Sweden. Three field trials with ware potatoes were also carried out in central west Sweden (location Vedum) from 2015 to 2017 and were managed by REAS, Skara, Sweden. The cvs. Gala and Fakse were used in 2015 and cv. Fakse in 2016 and 2017. The haulm killing was performed for the southern Sweden trials on September 5, 2015, and September 17, 2017. All ware potato trials were also designed as four completely randomized blocks, each plot being 18 m^2.

Management of Trials

All trial plots were treated against late blight according to standard practice. In most cases, that included weekly applications of Revus (a.i. Mandipropamid; 0.6

Table 2 Early blight field trial results from 2014 to 2023 showing the infection rate, defoliation rate and starch yield increase with best fungicide treatment or calculated potential starch yield increase if no disease

Year	Cultivar	Location	rAUDPC untreated	rAUC untreated	Untreated total yield (ton/ha)	Untreated starch yield (ton/ha)	Best fungicide total yield (ton/ha)	Best fungicide starch yield (ton/ha)	Starch Yield Increase			
									Best fungicide (ton/ha)	Calculated potential (ton/ha)	Best fungicide (%)	Calculated potential (%)
2014	Kuras	Nymö	0.431	0.684	53.6	10.9	58.8	12.3	1.37	2.30	12.6	21.1
2014	Kardal	Nymö	0.480	0.808	42.6	8.8	51.1	11.3	2.53	4.08	28.8	46.6
2016	Kuras	Nymö	0.117	0.239	81.5	17.5	87.1	18.8	1.35	1.67	7.7	9.5
2016	Stayer	Nymö	0.098	0.238	78.8	17.3	81.1	18.5	1.19	2.13	6.9	12.4
2016	Kuras	Helge	0.026	0.113	49.6	12.1	51.9	12.6	0.51	0.33	4.2	2.7
2016	Stayer	Helge	0.033	0.087	48.9	12.2	50.8	13.1	0.91	1.47	7.5	12.1
2017	Kuras	Nymö	0.104	0.283	78.4	16.7	81.1	17.1	0.37	0.57	2.2	3.4
2017	Kuras	Helge	0.025	0.102	71.6	15.8	73.5	16.7	0.88	0.80	5.6	5.0
2018	Kuras	Nymö	0.301	0.510	62.2	11.6	68.1	13.4	1.85	2.27	16.0	19.6
2018	Kuras	Helge	0.087	0.184	60.6	11.8	67.4	13.6	1.79	2.15	15.1	18.1
2019	Kuras	Nymö	0.198	0.375	63.6	13.0	70.3	15.4	2.40	3.37	18.5	26.0
2019	Kuras	Helge	0.086	0.193	54.7	10.6	60.0	12.0	1.41	1.77	13.4	16.8
2020	Kuras	Nymö	0.075	0.475	74.4	13.7	77.6	15.1	1.37	0.81	10.0	5.9
2020	Kuras	Helge	0.045	0.089	56.2	13.1	57.1	13.3	0.25	0.49	1.9	3.7
2021	Kuras	Nymö	0.038	0.269	74.1	14.6	76.0	15.0	0.43	0.57	2.9	3.9
2021	Kuras	Gärds Köpinge	0.109	0.393	71.3	13.6	86.4	16.5	2.89	2.42	21.2	17.7
2022	Kuras	Åsums boställe	0.034	0.617	59.1	15.6	76.6	19.5	3.93	3.11	29.9	23.6
2023	Kuras	Hovby	0.148	0.226	73.2	11.6	77.9	12.9	1.23	1.02	10.6	8.8

Table 2 (continued)

Year	Cultivar	Location	rAUDPC untreated	rAUC untreated	Untreated total yield (ton/ha)	Untreated starch yield (ton/ha)	Best fungicide total yield (ton/ha)	Best fungicide starch yield (ton/ha)	Starch Yield Increase			
									Best fungicide (ton/ha)	Calculated potential (ton/ha)	Best fungicide (%)	Calculated potential (%)
Mean all (18 trials):			0.135	0.327	64.1	13.4	69.6	14.8	1.48	1.74	11.9	14.3
Max			0.480	0.808	81.5	17.5	87.1	19.5	3.93	4.08	29.9	46.6
Min			0.025	0.087	42.6	8.8	50.8	11.3	0.25	0.33	1.9	2.7
SD all			0.136	0.215	11.7	2.5	12.1	2.5	0.97	1.08	8.4	11.0
CV % all			100	66	18	18	17	17	65	62	71	77
Mean Kuras (15 trials)			0.121	0.317	65.6	13.5	71.3	14.9	1.47	1.58	11.4	12.4
Max			0.431	0.684	81.5	17.5	87.1	19.5	3.93	3.37	29.9	26.0
Min			0.025	0.089	49.6	10.6	51.9	12.0	0.25	0.33	1.9	2.7
SD			0.113	0.186	9.9	2.1	10.7	2.4	1.01	1.00	7.9	8.3
CV %			93	59	15	16	15	16	69	63	69	67

L/ha) and RanmanTop (a.i. Cyazofamid; 0.5 L/ha) alternated at recommended doses. Occasionally, systemic late blight fungicides, i.e., Infinito (a.i. fluopicolide and propamocarb; 0.8 L/ha), were also used in high late blight pressure situations. No late blight infections that affected the trials were observed. Also, treatments against insects were applied in a standard way. Fertilisation was done according to general practice. In general, with slight variations, as follows: before planting, 1250 kg ha^{-1} of NPK 11–5–18 and 180 kg ha^{-1} of K25 KMg were added, and after planting, at the end of June, 160 kg ha^{-1}of Axan NS 27–4 was added as well. This corresponds to a total of 180 kg/ha N, 63 kg/ha P, and 270 kg/ha K. Additionally, for the first six weeks of late blight treatment, manganese was added as Mn235 at 1.5 L ha^{-1} (for ware potato trials in south Sweden 1 L/ha) 5–7 times during the season. Chemical treatments were applied with a special tractor trial sprayer with a water usage of 180–300 L ha^{-1} at 3.0 bar pressure with a flat fan nozzle medium droplet size. The fungicide product used in the starch potato trials varied over the years due to the development of fungicide resistance and the release of new products. Early blight fungicides and dose rates for all starch potato trials are given in Table 1. In the ware potato trials in south Sweden, Revus Top and Signum were used against early blight (Tables 4 and 5). In the trials in central west Sweden, either 2×Amistar (a.i. azoxystrobin; 0.5 L/ha) or 4×Signum (a.i. boscalid and pyraclotrobin; 0.25 kg/ha) were used according to the manufacturer's recommendations (Table 5).

Disease Assessment

Infections that occurred were natural since no inoculations were performed. The severity of early blight disease was visually assessed in percentage weekly or biweekly according to Duarte et al. (2013), and AUDPC and AUC (area under the defoliation curve) were calculated according to Shaner and Finney (1977). The rAUDPC was calculated by dividing AUDPC by the total area during the assessment period, assuming 100% disease from the start. Disease scoring data from 1 August until 15 September were used for the calculations in starch potato trials and from 1 August until 3 September in ware potato trials in south Sweden. In central west Sweden, the disease scoring was performed before harvest in mid-September. The disease score is the percent green leaf area that is covered with early blight lesions, and the defoliation score is the percentage of the whole plant that is dead or necrotised.

Yield and Starch Measurements

Yield and tuber starch content were measured at harvest by REAS for each plot and converted to kg ha^{-1}. Starch content was calculated according to the International Starch Institute, Denmark (1986) based on the specific weight.

Calculation of Yield Benefit by Fungicides and Potential Yield Loss

The yield benefit of using fungicides was calculated as the relative increase in yield compared to the untreated control. Specifically, it was determined using the formula:

$$\text{Yield gain (\%)} = [(\text{Yield fungicide} - \text{Yield untreated})/\text{Yield untreated}] \times 100$$

where only the best-performing fungicide treatment was used in the analyses. Each trial had 8 to 12 fungicide treatments with various efficacy on early blight. By plotting yield against infection rate (rAUDPC), a negative relation between infection rate and yield was established in each trial. The potential yield loss due to early blight infection was defined as the predicted yield from linear regression when no infection occurred (rAUDPC = 0).

Climate Data

In the starch potato trials, data on canopy air temperature and relative humidity (RH) were collected by placing Tinytag (Intab Stenkullen, Sweden; Model: Plus2 TGP-4505) within the crop's canopy about 40 cm above the soil surface on top of the furrow. In each trial, two Tinytags were placed with a distance of 50 m between them. The Tinytag recorded temperature and RH every 10 min. Daily mean gridded climate data, i.e., precipitation and air temperature measured 2 m above ground, was also obtained from the Swedish Meteorological and Hydrological Institute (SMHI) for each field trial location.

Calculation of the Economic Cost of Using Fungicides Against Early Blight

Currently grown potato cultivars require weekly fungicide applications for effective protection against late blight. To assess the economic feasibility of early blight control, only the current cost of early blight-specific fungicide products was considered (Lyckeby SSF data, oral communication), due to price variability over time and the illustrative nature of this analysis. Since early blight fungicides are typically mixed with late blight products and applied during the same spraying operations, no additional costs for machinery or labor were included.

For the calculation, we used the 2023 market price for starch potatoes, which was 1.08 SEK per kilogram of tubers at 20% starch content. The fungicide treatment strategy consisted of two applications of Revyona®, one application of Propulse®, and one of Narita®, totaling 1326 SEK per hectare. Based on these values, a starch yield increase of approximately 246 kg/ha would be required to offset the fungicide product cost. With an average tuber yield of 45,000 kg/ha and an assumed starch content of 20%, this corresponds to a required starch yield increase of 2.73% to economically justify the use of early blight-specific fungicides.

Statistical Treatment

Correlations between parameters (Starch yield, starch yield increase, rAUDPC, rAUC, DAP10%, Air Temp, Soil sand content) were investigated with Pearson correlation coefficient. Differences in infection rate and yield between the sites Nymö and Helgegården were analysed with ANOVA (SAS version 9.4). The effect of weather factors and soil sand content on infection rate, yield in untreated plots, yield in fungicide treated plots, and yield increase by fungicide treatment was analysed with stepwise regression with R (function step()). (R Core Team (2023)). In the ware potato trials, the effect of fungicide treatment on infection rate and yield was investigated with ANOVA/GLM followed by Tukey test (SAS Version 9.4).

Results

Yield and Yield Loss Due to Early Blight in Starch Potato

Among all 18 trials (2014–2023), starch yield in untreated plots varied between 8.8 and 17.5 tons ha^{-1} with an average of 13.4 tons ha^{-1} (Table 2). The starch yield increased for the best fungicide treatment within each trial compared to the untreated plots, ranging from 0.25 to 3.93 tons ha^{-1} with an average of 1.48 tons ha^{-1}. The calculated potential yield increases were higher. In percentages, the yield increase by the best fungicide was, on average, 11.9% but varied largely among trials from 1.9 to 29.9% depending on year, field site, cultivar, climate, and other factors. The corresponding values for the calculated potential yield increase were 14.3% on average, ranging from 2.7 to 46.6%. Most trials were carried out at the Nymö and Helgegården sites. At Nymö, the infection rates (rAUDPC) were higher than on Helgegården (Anova F = 12.0, p = 0.026), and that was also reflected in the starch yield increase by the best fungicide treatment, which was, on average, 1.47 tons ha^{-1} at Nymö and 0.97 tons ha^{-1} at Helgegården in cultivar Kuras (Supplementary Table 2).

Yield and Yield Loss Due to Early Blight in Ware Potato

In total, six trials were carried out with ware potato, with two trials at the same sites as the starch potato trials in south Sweden and three trials in Västergötland, central west Sweden. In 2015, two cultivars (Bintje and Folva) were used at Helgegården and Nymö. There was a significantly lower infection rate in the fungicide-treated plots, but no significant effect on yield was observed (Table 3). A similar trial was carried out in 2017 at Nymö (Table 4), but an uneven number of replicates due to a mistake in the planting affected the statistical analysis for this trial. However, no significant yield increase was found. The tendency to yield increase seemed to be associated with late haulm killing and harvest, resulting in a higher proportion of oversized tubers. The fungicide treatment significantly increased the proportion of oversized tubers in both Bintje and Folva cultivars in the > 65 mm tuber size

Table 3 Effect of fungicide treatments on early blight severity and yield in field trials with ware potato cvs. Bintje and Folva at two sites in south Sweden 2015

Treatment	Yield (ton/ha)	rAUDPC	rAUC defoliation
Nymö, Bintje			
Untreated control	61.8	0.045	0.306
Revus Top (T1, T2); Signum (T3, T5, T7, T9)	59.2	0.007	0.301
Revus Top (T1, T2); Signum (T3, T5, T7, T8, T9, T10)	57.6	0.007	0.295
Nymö, Folva			
Untreated control	72.9	0.022	0.190
Revus Top (T1, T2); Signum (T3, T5, T7, T9)	68.6	0.008	0.184
Revus Top (T1, T2); Signum (T3, T5, T7, T8, T9, T10)	70.5	0.009	0.198
Helgegården, Bintje			
Untreated control	75.5	0.125	0.446
Revus Top (T1, T2); Signum (T3, T5, T7, T9)	75.5	0.054	0.397
Revus Top (T1, T2); Signum (T3, T5, T7, T8, T9, T10)	76.6	0.074	0.426
Helgegården, Folva			
Untreated control	86.4	0.036	0.163
Revus Top (T1, T2); Signum (T3, T5, T7, T9)	88.8	0.021	0.137
Revus Top (T1, T2); Signum (T3, T5, T7, T8, T9, T10)	87.9	0.020	0.152
Mean all			
Untreated control	74.2[a]	0.057[a]	0.276[a]
Revus Top (T1, T2); Signum (T3, T5, T7, T9)	73.0[a]	0.022[b]	0.255[a]
Revus Top (T1, T2); Signum (T3, T5, T7, T8, T9, T10)	73.1[a]	0.027[b]	0.268[a]

[*]Different letters indicate significant difference according to Tukey test. The fungicide active ingredients and dose rates are provided in brackets: Revus Top (Difenoconazole + Mandipropamid; 0.6 L/ha) and Signum (Boscalid + Pyraclostrobin; 0.25 kg/ha)

category. In Bintje, the proportion rose from approximately 9% in the untreated to 18% following treatment. Similarly, in Folva, the percentage of tubers exceeding 65 mm increased from about 18 to 31% with fungicide application (Supplementary Fig. 2). The infection rate was very low at all three field trials in central west Sweden carried out in Vedum from 2015 to 2017 (Table 5). We did not find any effect of fungicide treatment on yield in any of the trials, and there was no overall significant effect on yield.

Relation Between Infection Rate and Yield increase by Fungicide Treatment

We found no general change in infection rate over the years, but the highest infection rate was recorded in 2014. There was a negative correlation between infection rate and starch yield (Fig. 1a; $R^2 = 0.302$, $p = 0.018$) and between defoliation rate

Table 4 Effect of fungicide treatments on early blight severity and yield in field trials in Nymö, south Sweden with ware potato cvs. Bintje and Folva 2017

Treatment	N	Yield (ton/ha)	rAUDPC	rAUC defoliation
Bintje				
Untreated control	2	62.9	0.091	0.476
RevusTop T4, T8, T12; Signum T6, T10	6	65.5	0.043	0.429
Folva				
Untreated control	6	72.4	0.035	0.334
RevusTop T4, T8, T12; Signum T6, T10	2	76.8	0.007	0.204
Mean				
Untreated control		67.7[a]	0.063[a]	0.405[a]
RevusTop T4, T8, T12; Signum T6, T10		71.1[a]	0.025[a]	0.317[a]

The fungicide active ingredients and dose rates are provided in brackets: Revus Top (Difenoconazole + Mandipropamid; 0.6 L/ha) and Signum (Boscalid + Pyraclostrobin; 0.25 kg/ha); Different letters indicate significant differences according to Tukey test

Table 5 Effect of fungicide treatment against early blight in ware potato in field trials in central west Sweden (Vedum) 2015–2017

Year	Cultivar	Treatment	Defoliation (%)	Yield (ton/ha)
2015	Fakse	Control	32.5	58.2
		Amistar	29.3	60.5
		Signum	39.5	57.4
	Gala	Control	68.8	49.8
		Amistar	83.0	52.7
		Signum	69.5	51.5
2016	Fakse	Control	17.0	60.4
		Amistar	30.0	57.0
		Signum	17.7	56.0
2017	Fakse	Control	n.d	30.7
		Amistar	n.d	29.2
		Signum	n.d	30.4

n.d., not determined. The fungicide active ingredients and dose rates are provided in brackets: Amistar (Azoxystrobin; 0.5 L/ha), Signum (Boscalid + Pyraclostrobin; 0.25 kg/ha)

and starch yield (although not significant; Fig. 1b; $R^2 = 0.099$, $p = 0.21$) in untreated plots over all 18 trials. However, at lower infection rates, the yield in untreated plots seemed to vary largely due to other factors like weather and soil properties. There was a positive correlation between yield increase due to fungicide treatment and the infection rate (rAUDPC) in untreated plots. However, that was only statistically significant with the calculated potential yield increase (Fig. 1c; $R^2 = 0.395$, $p = 0.005$). The starch yield increase due to fungicide treatment was better correlated with the total defoliation rate in untreated plots (rAUC) (Fig. 1d), where highly significant values were found for both best fungicide yield increase and calculated potential yield increase ($R^2 = 0.416$, $p = 0.0039$ and $R^2 = 0.493$, $p = 0.0012$, respectively).
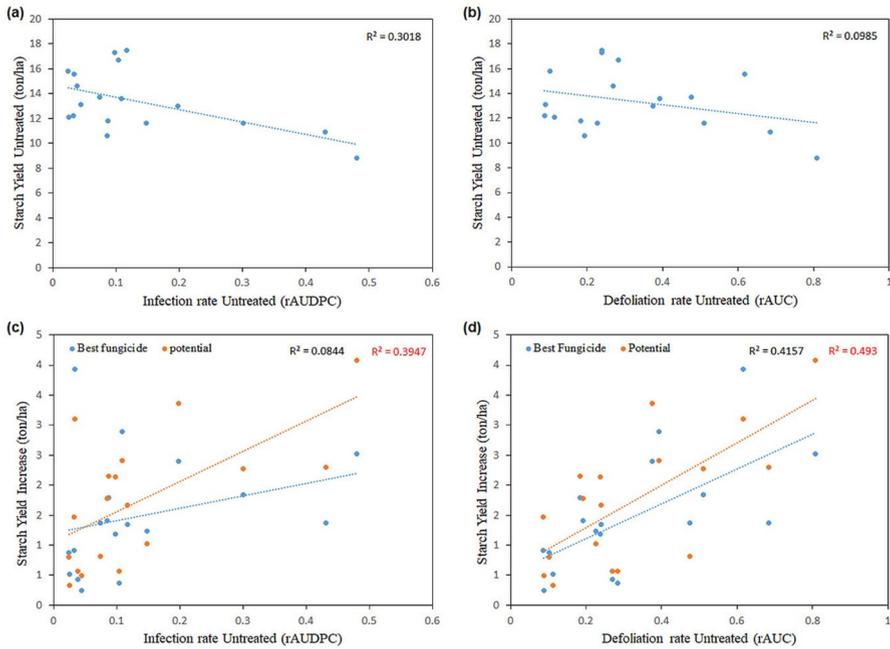
Fig. 1 Starch yield in untreated plots and starch yield increase by fungicide treatment and potential in relation to infection rate and defoliation rate in field trials 2014–2023
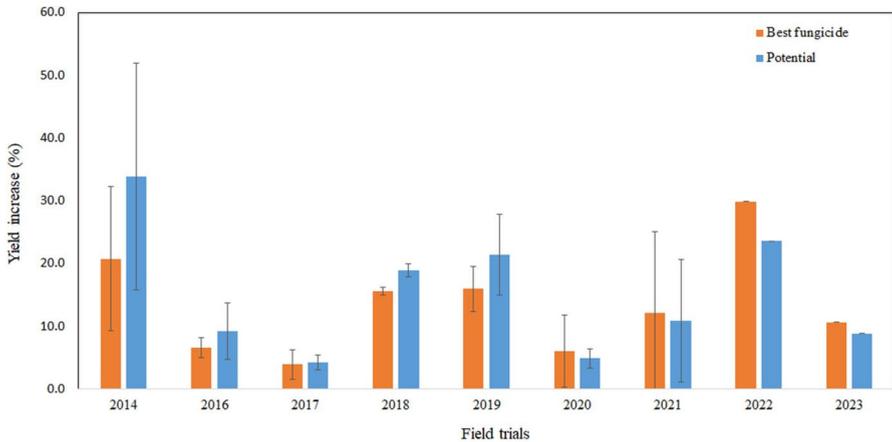

Fig. 2 Average yield increase by best fungicide practice and calculated potential yield increase if no disease over years 2014–2023

Yield Increase by Treatment over Years

The starch yield increase with fungicide treatment varied over the years (Fig. 2). Notably, lower yield increases were observed during 2016–2017, 2020, and 2023.

Additionally, the calculated potential yield increase was higher than the observed yield increase achieved with best fungicide application at the beginning of the trial period. However, from 2020 onwards, the calculated potential yield increase was similar to or lower than the observed yield increase. This trend aligns with the introduction and utilisation of fungicides with higher efficacy during the later years of the study (Tables 1 and 2).

Yield Increase by Fungicide Treatment in Relation to Earliness of Infection

As a measure of how early in the season the epidemiological phase of infection started, we calculated the number of days after planting (DAP) where a 10% infection rate was reached. A significant negative correlation was observed between DAP at 10% infection rate and calculated potential starch yield increase (Fig. 3a; $R^2 = 0.379$, $p = 0.0065$). Considering the potential influence of yield increase with site and cultivar, this correlation was further examined at the site Nymö using cv. Kuras across seven trials. Here, the correlation coefficients were notably higher, with $R^2 = 0.385$ ($p = 0.13$) for the best fungicide yield increase and $R^2 = 0.601$ ($p = 0.041$) for the calculated potential yield increase (Fig. 3b).

Infection Rate and Treatment Yield Increase in Relation to Weather

Local air temperature and RH were recorded in almost all trials using the Tinytag datalogger positioned within the crop canopy. Mean canopy air temperature and RH were calculated for the period from 1 July until 15 August from all trials, except for 2023. These variables were correlated with infection rates in untreated plots and yield increase to fungicide treatment (Fig. 4). A significant positive correlation was identified between mean air temperature within the canopy and infection rates in untreated plots (Fig. 4a; $R^2 = 0.305$, $p = 0.021$). Additionally, a significant negative relationship was observed between mean canopy air temperature and starch yield in
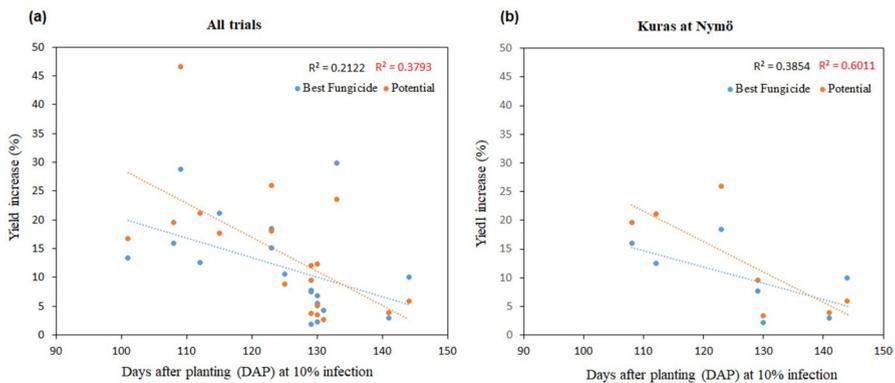
Fig. 3 Yield increase (by best fungicide treatment and potential) in relation to earliness of infection (DAP at 10% infection)
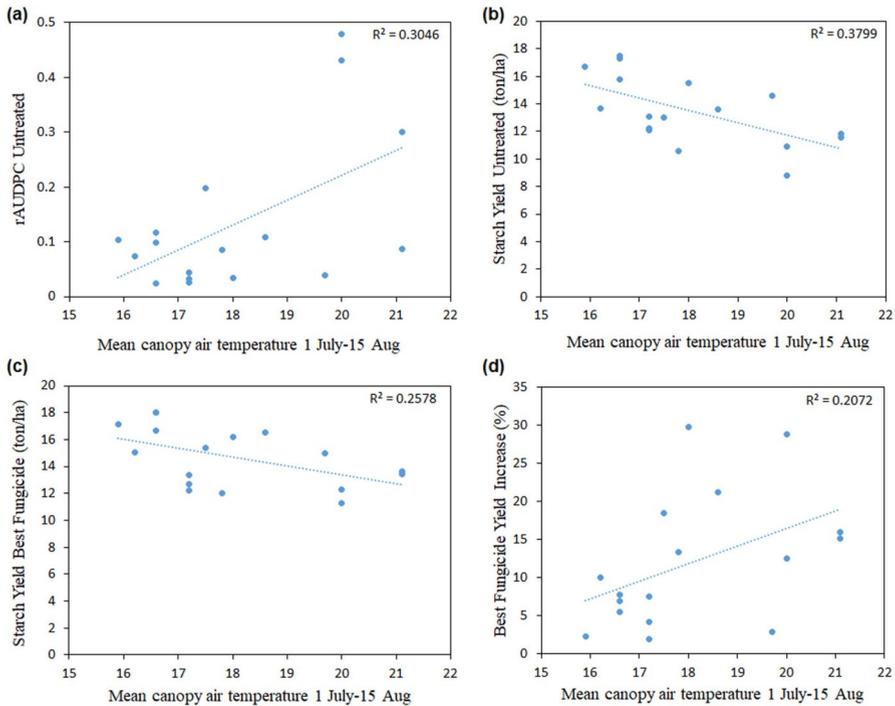
Fig. 4 Infection rate (rAUDPC), yield, and yield increase as response to fungicide treatment in relation to season mean air temperature measured within canopy (Tinytag) or to SMHI gridded data

untreated plots (Fig. 4b; $R^2 = 0.380$, $p = 0.008$), as well as with starch yield in fungicide-treated plots (Fig. 4c; $R^2 = 0.258$, $p = 0.028$). However, a positive correlation was observed with the yield increase with the best fungicide treatment and the mean canopy air temperature (Fig. 4d; $R^2 = 0.207$, $p = 0.066$). There was no significant correlation found between season average RH and infection rate (data not shown).

The climate data, measured with Tinytag sensors placed within the plant canopy, were compared with gridded climate data from SMHI, specifically on mean air temperature and total precipitation during the same period. Correlation analysis between temperature, infection rate, and yield using SMHI data gave similar, although somewhat less significant, results (Supplementary Fig. 1a-d). To further investigate the impact of climatic conditions, we also examined the relationship between infection rate and yield loss with air temperature and precipitation during June, August, and September, as well as the mean values across these months. These additional analyses revealed nonsignificant relationships (data not shown).

Infection Rate and Treatment Yield Increase in Relation to Soil Sand Content

Earlier farm observational studies (Stridh et al. 2023) indicated that potatoes grown in soils with a high sand content are more prone to early blight infections. To further

Fig. 5 Infection rate, defoliation rate, and best fungicide yield increase in relation to soil sand content
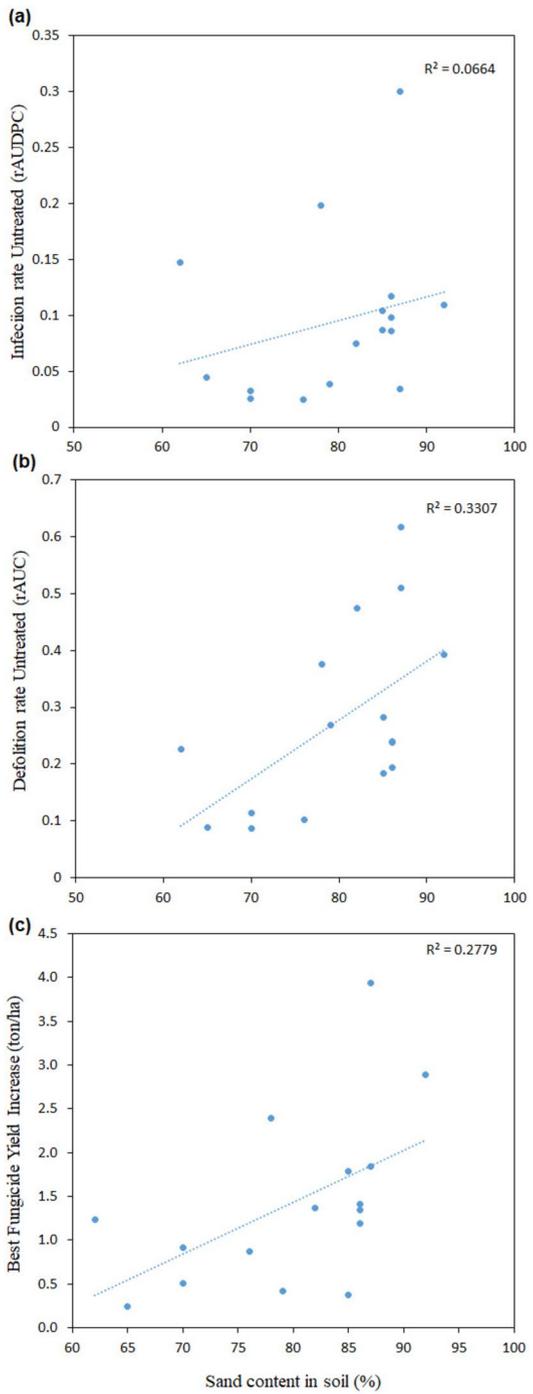
investigate this association, we analyzed the relationship between sand content in soil and infection rate in the current trials (Fig. 5). The results indicated that infection and defoliation rates were notably lower in the soils with sand content below 75% (Fig. 5a and b). Conversely, in soils with higher sand content, the increase in yield due to fungicide treatment was significantly greater (Fig. 5c; $R^2 = 0.278$, $p = 0.036$).

Economic Benefit of Fungicide Treatment Against Early Blight

The threshold starch yield increase required to compensate for the early blight fungicide product cost was calculated at approximately 250 kg of starch per hectare, corresponding to a 2.7% starch yield increase (Table 2). Across the 18 trials conducted, the cost benefit threshold was achieved in 14 trials, while it was not met in two cases and marginally achieved in two other trials. In contrast, the ware potato trials did not show a statistically significant yield increase in response to early blight fungicide application.

Statistical Modelling of Factors Influencing Infection and Yield

Stepwise regression analysis was performed to understand the relationships between infection rate (rAUDPC), yield in fungicide untreated plots, yield in fungicide treated plots, yield increase with fungicide treatment, and key environmental and soil variables such as mean canopy air temperature, relative humidity, precipitation, and soil sand content. This analysis was restricted to cultivar Kuras.

For rAUDPC, the best model turned out to be with only mean canopy air temperature (Tinytag). However, the relationship for temperature was not statistically significant ($p = 0.168$), and the model explained only 16.5% of the variation. The estimated function was:

$$\text{rAUDPC} = -0.25 + 0.018 \times \text{Temp.}$$

For untreated starch yield, the best model was with RH as the only independent variable ($p = 0.035$), accounting for 34% of the variation. The estimated function was:

$$\text{Untreated starch yield} = -6.71 + 0.24 \times \text{RH.}$$

For fungicide-treated starch yield, the best model included both RH and soil sand content. However, there was only a significant relationship for RH ($p = 0.038$), accounting for 35% of the variation followed by soil sand content (9%). The estimated function was:

$$\text{Fungicide treated starch yield} = -10.44 + 0.22 \times \text{RH.}$$

For fungicide-treated starch yield increase, the best model included soil sand content and total precipitation. Soil sand content showed a significant relationship

($p = 0.020$), as 38% of the variation was explained by soil sand content followed by precipitation (11%). The estimated function was:

Fungicide treated starch yield increase $= -4.46 - 0.015 \times \text{precipitation} + 0.09 \times \text{sand}$.

Discussion

The application of fungicide treatments targeting early blight in starch potato cultivation demonstrated a significant impact on starch yield, but varied largely across multiple trials. The observed yield increase ranged from 1.9 % to 29.9%, with an average enhancement of 11.9%. The calculated potential starch yield increase was higher, 14.3% on average, reflecting minor infections that also occurred in fungicide-treated plots. This discrepancy highlights underlying factors influencing disease progression and yield loss even under fungicide treatments. There are few published reports on yield losses due to early blight in potato (Yellareddygari et al. 2018; Leiminger and Hausladen 2012; Olanya, 2009; Shtienberg et al. 1990). Our results align with or are somewhat lower than the yield loss estimates reported by Leiminger and Hausladen (2012) for trials conducted in Germany. In historical literature, a wide range of yield loss was reported from 5 % to 50% (Neergaard 1945). Shtienberg et al. (1990) cited several earlier reports indicating yield losses of up to 20–30% in the USA. Similarly, Olanya (2009) documented yield reductions of 5–40% in Israel due to early blight. Thus, the range of variability observed among these studies and the current study indicates the complex interactions among factors such as environmental conditions, disease pressure, and cultivar susceptibility influencing infection rate and subsequent yield.

Shtienberg et al. (1990) developed and evaluated a general model for yield loss assessment in potato using data from many early blight and late blight epidemics in the USA. They concluded that rAUDPC was an adequate predictor of yield and yield loss in potato. They considered loss as a function of rAUDPC multiplied by the effect of disease on bulking rate. In our trials, a negative correlation between rAUDPC and starch yield was evident, although the correlation was weak at low infection rates, likely due to several other factors affecting yield loss.

Between 2015 and 2017, six trials were conducted on ware potatoes to evaluate the effects of fungicide treatments against early blight. No statistically significant increase in yield was observed in any of the trials. In one trial, there was a tendency for higher yields with fungicide treatment, but that was attributed to delayed haulm killing. This delayed haulm killing resulted in a higher proportion of oversized tubers, which is generally not an advantage on the market.

In starch potato trials, the discrepancy between the observed and the calculated yield increase could be attributed to the limited efficacy of the fungicide treatments, particularly during the early phase of the study. However, that was mainly the case when boscalid and difenoconazole were used at the beginning of the trial. In 2014 and 2015, efficacies of around 60% were observed, which became even lower in 2016 due to the development of fungicide resistance against boscalid

(Mostafanezhad et al. 2021). In the later years, the introduction of new fungicide products with fluopyram and mefentrifluconazole as active ingredients was released, resulting in efficacies above 80% and up to 98% efficacy. During this later period, no difference between the observed and calculated yield increase was observed. Therefore, at the beginning of the period, the actual yield losses were underestimated by only comparing yield in untreated and yield with fungicide treatment, suggesting that under effective fungicide regimes, yield loss estimates based on untreated versus treated plots become more accurate.

Starch yield increase due to fungicide treatment against early blight varied largely with year and trial site. We found a clear positive correlation between earliness of infection, i.e., the start of the epidemiological phase of infection measured as DAP at 10% infection rate, and yield loss due to early blight. Yellareddygari et al. (2018) examined the relationship between early blight severity and tuber yield from 23 ware potato field trials between 2003 and 2016 in the Midwestern USA and discovered a negative correlation between early blight severity and yield. However, there was a large variability. Infections during early stages (tuber initiation) had a more significant yield effect than those during late bulking/tuber maturation. This is in accordance with our observation that the earliness of infection showed a strong positive correlation with yield loss.

The variation in average infection rates between the Helgegården and Nymö sites may be explained by the differences in soil composition, particularly sand content. Helgegården, characterised by lower sand content, exhibited lower average infection rates compared to the sandy soils at Nymö. This observation aligns with findings from Stridh et al. (2023), who reported in a field study that potato grown on soils with higher sand content were more prone to severe early blight infections. Similarly, in our current investigation, we observed that high infection rates were predominantly observed at trial sites with high sand content. This suggests that the higher sand content might influence soil water retention and aeration, creating conditions more conducive to the development and progression of early blight. These findings underscore the role of soil physical properties, particularly sand fraction, as a critical factor influencing early blight severity in potato cultivation. Future studies could delve deeper into the interplay between soil characteristics and pathogen dynamics to better inform site-specific disease management strategies.

We did not find any obvious changes in infection rate between 2014 and 2023. However, a positive correlation between average seasonal air temperature and infection rate in untreated plots was evident, although this correlation did not show statistical significance in the stepwise regression analysis. This suggests that temperature likely plays a role in modulating infection dynamics, but other contributing factors may also obscure this relationship. Interestingly, the variation in rAUDPC was much higher at higher temperatures (Fig. 4). At low temperatures, very high infection rates were not observed, indicating a possible higher mean temperature threshold beyond which the pathogen's activity and the disease progression intensified significantly. There was a negative correlation between average seasonal air temperature and starch yield in both untreated and fungicide-treated plots. This indicates that early blight is favoured at higher average daily temperatures, which may partly explain the reduced yield benefits observed in cooler years such as 2016–2017 and

2020, where lower temperatures potentially limited the disease's severity. Notably, the stepwise regression analysis identified RH as a significant factor influencing yield. However, there was a highly significant negative correlation between RH and mean temperature ($R^2 = -0.64$, $p = 0.0001$), indicating that as temperature increases, RH typically decreases. The regression model favoured RH over temperature as a predictor due to its slightly stronger correlation with yield, but this choice reflects the intertwined relationship between these variables rather than RH acting independently. Since fungicide-treated plots tended to have lower yields at higher temperatures, this raises concerns about the adaptability of currently used potato cultivars to warmer conditions. High temperatures may negatively impact cultivar performance, potentially through physiological stress or reduced starch accumulation rates (Paul et al. 2017; Rykaczewska 2015). Moreover, it is also possible that the lower RH at higher temperatures may exacerbate this effect by impairing photosynthesis. Specifically, reduced RH often results in more frequent stomatal closure that restricts CO_2 uptake, thereby limiting photosynthetic efficiency and carbon assimilation, compounding the adverse effects of dual stress on potato growth and starch yield (Zhang et al. 2022; Kim & Lee 2019; Aien et al. 2017).

No significant correlation was found between infection rate and average RH or total precipitation during the critical period of 1 July to 15 August. However, high RH is an essential factor for infection, likely facilitated by night and morning dew, which may provide enough time for high humidity conditions for pathogen establishment. Further analysis of the duration of high RH during nighttime may unravel correlations to infection rate. Escuredo et al. (2019) analyzed data on the distribution pattern of spores of *A. solani* and *A. alternata* across eight potato growing cycles in North-West Spain between 2017 and 2019. They reported that the concentration of *Alternaria* sp. spores in the air was higher at a mean temperature above 20 °C and a mean RH level below 70%. Furthermore, they pointed out that lower temperatures and higher humidity at night favoured spore production during the day. This supports our observation of higher early blight severity at higher mean temperatures and suggests a strong interplay between temperature, RH, and spore dynamics. This reinforces the concern that with continued climate change and rising mean temperatures, we may expect more severe early blight epidemics across the potato growing fields worldwide. Jindo et al. (2021) and Rotem (1994) provide further context, noting that the optimum temperature range for early blight infection lies between 20 and 30 °C. These insights highlight the complex interactions between climatic variables and early blight dynamics, necessitating adaptive disease management strategies in light of global warming.

Conclusion

Careful estimations of yield losses are essential for evaluating the economic feasibility of using fungicides against early blight. Our results show that a standard schedule of four fungicide applications is generally cost-effective in starch potato cultivation in regions prone to severe early blight epidemics. However, in fields with lower infection risk, such as those with lower soil sand content documented by Stridh et al. (2023), fewer applications may be sufficient and result in a better economy. Overuse of fungicides remains

a critical concern, potentially accelerating resistance development and having a negative environmental impact. We also conclude that for ware potatoes harvested before late August, the use of fungicides against early blight is not economically feasible under current conditions in Sweden. However, the projected impacts of climate change, including higher temperatures and potentially earlier, more severe infections, may necessitate a re-evaluation of this conclusion in the future. Across diverse potato-growing regions, from temperate climates in Europe to tropical and subtropical zones, adaptive approaches to early blight management will be vital. Integrating site-specific agronomic practices, improved cultivar selection, and the judicious use of fungicides will ensure economic sustainability while mitigating environmental risks on a global scale.

Declarations

Ethical Approval and Consent to Participate Not applicable.

Consent for Publication The authors agreed to publish this paper.

Competing interests The authors declare no competing interests.

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