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Article

Genotype and Fungicide Treatment Interactions Affect Potato Late Blight Development and Yield under Field Conditions

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Abstract

Potato late blight, caused by *Phytophthora infestans*, remains a major constraint to potato production worldwide. This study evaluated the interaction between climatic conditions, genotype, and fungicide treatment schemes on disease development and yield under field conditions over three growing seasons (2022–2024). A factorial experiment including four cultivars and five fungicide treatment schemes was conducted. Disease severity was assessed using the area under the disease progress curve (AUDPC), along with yield and tuber size distribution. Disease progression followed a sigmoidal pattern, with rapid development during flowering and tuber bulking stages. Disease severity was influenced more by the timing of favorable environmental conditions than by total precipitation. Significant differences in AUDPC among genotype × treatment combinations indicated cultivar-specific responses to fungicide treatment schemes. Yield was significantly affected by year, genotype, and treatment ($p < 0.001$), but showed a weak relationship with disease severity ($R^2 = 0.002$), indicating that disease intensity alone did not determine yield outcomes. Instead, genotype performance and treatment efficiency were the main determinants. These results emphasize the importance of integrating cultivar selection with optimized fungicide treatment schemes for effective late blight management under field conditions.

Keywords: potato late blight; *Phytophthora infestans*; plant disease management; AUDPC; fungicide treatment schemes; genotype × environment interaction; crop yield

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the most important food crops worldwide, contributing significantly to global food security and agricultural sustainability [1–3]. However, potato production is severely constrained by plant pathogens, among which late blight, caused by *Phytophthora infestans*, remains the most destructive disease globally, capable of causing yield losses exceeding 50% under favorable conditions [3–7].

The development and severity of late blight epidemics are influenced by environmental conditions, particularly the interaction between temperature, precipitation, and relative humidity [4,5,8,9]. While numerous studies have highlighted the importance of climatic factors in disease development, increasing evidence suggests that the temporal distribution of favorable conditions, rather than cumulative seasonal values, plays a critical role in epidemic dynamics [5,10–14].

In addition to environmental drivers, the effectiveness of disease control strategies depends on complex interactions between host genotype and fungicide treatment schemes [7–18]. Although integrated management strategies combining resistant cultivars and fungicide applications are widely recommended, their efficiency varies considerably depending on cultivar-specific responses and local agro-climatic conditions [10–14].

Despite extensive research on potato late blight, multi-year field studies integrating genotype × treatment interactions with detailed epidemiological analysis remain limited for Eastern European regions, particularly under the specific climatic conditions of Northern Romania [26,27]. Moreover, the relationship between disease severity indicators such as AUDPC and crop yield remains insufficiently understood under field conditions [14,19–25, 28-31].

Therefore, the objectives of this study were:

(i) to evaluate the development of potato late blight under field conditions over multiple growing seasons,

(ii) to assess the combined effects of genotype and fungicide treatment schemes on disease severity, and

(iii) to analyze the relationship between epidemiological indicators and potato yield under variable climatic conditions.

2. Materials and Methods

2.1. Experimental Site

Field experiments were conducted over three consecutive growing seasons (2022–2024) at the Agricultural Research and Development Station of Suceava, located in Northern Romania at the following geographical coordinates: latitude 47°38.16′N, longitude 26°14.40′ E, at an altitude of 360 m. The soil is of chernozem-like type, characterized by specific levels of macro- and microelements, as well as organic matter content.

The soil at the experimental site is classified as a cambic chernozem, with medium fertility, a loamy texture, and a pH ranging between 6.2 and 6.4. Standard agronomic practices for potato cultivation in the region were applied uniformly across all experimental variants, including soil preparation and fertilization.

Daily climatic data, including air temperature, precipitation, and relative humidity, were recorded using a meteorological station located within 500 m of the experimental field.

2.2. Plant Material

The four potato (*Solanum tuberosum* L.) genotypes included in the study (Darilena, Red Lady, Riviera, and Temerar) are commonly cultivated in the region and differ in their agronomic performance and susceptibility to late blight.

2.3. Experimental Design and Fungicide Treatment Schemes

The experiment was established as a two-factor factorial design arranged in a random complete block design (RCBD) with three replications.

The experimental factors were:

- Factor A: Genotype (four levels: Darilena, Red Lady, Riviera, Temerar)
- Factor B: Fungicide treatment scheme (five levels: B1–B5)

Each replication (block) included all possible combinations of the two factors, resulting in 20 experimental plots per block (4 genotypes × 5 fungicide treatment schemes).

Each experimental plot had an area of 24 m² and consisted of four rows, each 8 m in length.

For each genotype, the five fungicide treatment schemes occupied a total area of 120 m². Consequently, the total area of each replication was 480 m².

Across the three replications, the experiment comprised a total of 60 experimental plots.

The planting density was approximately 53,000 plants ha^{-1}, with a row spacing of 75 cm and an intra-row spacing of 25 cm.

The buffer zones were established between plots to minimize spray drift and treatment interference.

The layout of the experimental design is presented in Figure 1.

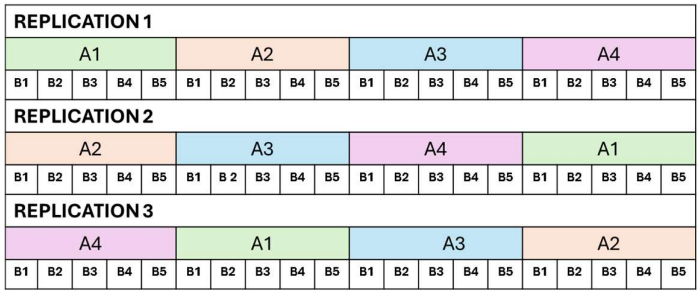


Figure 1. Schematic representation of the experimental design arranged in a randomized complete block design (RCBD) with three replications. Each block includes four potato genotypes (A1=Darilena, A2=Red Lady, A3=Riviera, and A4=Temerar), each subjected to five fungicide treatment schemes (B1–B5). Each experimental plot has an area of 24 m².

The fungicide treatment schemes were as follows:

B1 – Preventive systemic treatment (6 applications): applied at 10-day intervals between BBCH growth stages 35–39. Active substances were alternated and included: fluopicolide + propamocarb hydrochloride (Infinito, 62.5 + 625 g L^{-1}) at 1.4 L ha^{-1}, mandipropamid + difenoconazole (Carial Star 250 + 250 g L^{-1}) at 0.6 L ha^{-1}, oxathiapiprolin + benthiavalicarb (Zorvec Endavia) at 0.4 L ha^{-1} (applied in 2022–2023) and oxathiapiprolin + amisulbrom (Zorvec Entecta) at 0.25 L ha^{-1} (applied in 2024).

B2 – Curative systemic treatment (6 applications): applied weekly starting at the first appearance of disease symptoms (BBCH 50–55). The same fungicides as in B1 were used, but applications began after symptom onset.

B3 – Systemic + contact treatment (6 applications): applied at 10-day intervals between BBCH growth stages 40–49: mandipropamid + difenoconazole (Carial Star 250 + 250 g L^{-1}) at 0.6 L ha^{-1}, copper hydroxide (Champ 77 WG, 50%) at 2 kg ha^{-1}, fluopicolide + propamocarb hydrochloride (Infinito, 62.5 + 625 g L^{-1}) at 1.4 L ha^{-1}, fluazinam (Nando 500 g L) at 0.4 L ha^{-1}, followed by repetition of the treatment sequence until six applications were completed.

B4 – Contact treatment (6 applications): alternating applications of Champ 77 WG at 2 kg ha^{-1} and Nando at 0.4 L ha^{-1} applied at 10-day intervals until six applications were completed.

B5 – Untreated control: no fungicide treatments applied.

All fungicide treatments were applied using a backpack sprayer under field conditions, with a spray volume of approximately 300 L ha^{-1}, ensuring uniform canopy coverage.

2.4. Disease Assessment

Disease development was monitored through seven sequential assessments during the growing season, corresponding to key phenological stages defined according to the BBCH scale (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie). These stages corresponded to the main phenological phases of potato development and disease progression: (1) early leaf development, (2) leaf canopy development, (3) stem elongation and beginning of row closure, (4) advanced vegetative growth and tuber initiation, (5) tuber growth and inflorescence development, (6) beginning of flowering accompanied by tuber growth, and (7) full flowering stage associated with tuber bulking.

At each assessment, twenty plants per plot (N = 20) were randomly selected and evaluated.

Disease severity was quantified using the following epidemiological indicators:

- **Frequency of attack (F%)**

The frequency of attack was expressed as the percentage of plants showing visible late blight symptoms relative to the total number of evaluated plants, according to standard epidemiological procedures [19,32,33]:

F% = (Number of infected plants/Total number of assessed plants) x 100

- **Intensity of attack (I%)**

Disease intensity was estimated visually using a rating scale from 0 to 5, corresponding to the percentage of leaf area affected by the disease on infected plants.

Visual severity scales are widely used in plant disease epidemiology and are considered a reliable method for estimating disease intensity under field conditions [17,32,34].

- **Degree of attack (GA%)**

The degree of attack was used as an integrated indicator describing disease severity at crop level and was calculated using the following formula:

$$GA\ (\%) = (F \times I) / 100$$

where `F` represents the frequency of attack (%) and `I` represents the intensity of attack (%). The GA values recorded during successive disease assessments were used for further epidemiological analysis [28 ,35].

2.5. Disease Progress Evaluation (AUDPC)

To evaluate disease progression during the growing season and allow objective comparisons among experimental variants, the area under the disease progress curve (AUDPC) was calculated based on the degree of attack values recorded during successive disease assessments [32,33].

$$AUDPC = \Sigma\ [(Yi + Yi+1) / 2] \times (ti+1 - ti)$$

where Yi represents the disease severity (degree of attack) recorded at the i-th observation, Yi+1 represents the disease severity at the next observation, and (ti+1 − ti) represents the time interval between two successive observations.

To facilitate comparisons among experimental variants and growing seasons, the relative AUDPC (rAUDPC) was also calculated by expressing AUDPC values as a percentage of the maximum possible AUDPC value [15, 36,37].

2.6. Yield Assessment

At harvest, tubers were collected from each experimental plot, and total yield was determined and expressed in t ha^{-1}. These data were used to assess the effects of genotypes, fungicide treatment schemes, and environmental conditions on crop productivity [38,39].

2.7. Tuber Size Distribution

Tubers were classified into three size categories based on diameter: <35 mm, 35–55 mm, and >55 mm. The yield corresponding to each fraction was recorded and expressed in t ha^{-1}.

2.8. Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics software.

A three-way analysis of variance (ANOVA) was used to evaluate the effects of year, genotype, and treatment scheme on disease severity (AUDPC) and potato yield. The model included all main effects and their interactions.

Mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at $p < 0.05$.

Regression analysis was performed to assess the relationship between disease severity (AUDPC) and potato yield. The coefficient of determination (R^2) was used to evaluate the strength of the relationship.

3. Results

3.1. Climatic Conditions during the Growing Season

Climatic conditions during the potato growing seasons differed among the experimental years (Table 1). The mean air temperature recorded during the May–August period ranged from 19.10°C in 2023 to 20.64°C in 2024. Total precipitation was highest in 2022 (293 mm), while considerably lower amounts were recorded in 2023 (211.43 mm) and 2024 (167.60 mm). Relative humidity varied between 60.43% and 66.75%, with the highest value observed in 2023.

Table 1. Climatic conditions during the growing season (May–August) in the experimental field in three consecutive years (2022-2024).

Year	Mean temperature (°C)	Precipitation (mm)	Relative humidity (%)
2022	19.87	293.00	60.43
2023	19.10	211.43	66.75
2024	20.64	167.60	62.08

Note: Climatic values represent mean temperature, cumulative precipitation and mean relative humidity, recorded during growing period of potato (May–August).

Despite the higher total precipitation recorded in 2022, this year was associated with the lowest disease severity (rAUDPC = 28.96%), whereas the highest disease levels were observed in 2024 (rAUDPC = 41.72%) (Table 2). This suggests that total seasonal precipitation alone did not explain the observed differences in epidemic development.

Table 2. Mean AUDPC and relative AUDPC values recorded during the experimental years.

Year	Mean AUDPC	Mean rAUDPC (%)
2022	281.15	28.96
2023	357.90	35.49
2024	516.83	41.72

Note: AUDPC – area under the disease progress curve; rAUDPC – relative AUDPC expressed as percentage of the maximum possible value.

A more detailed analysis of daily climatic data revealed important differences in the temporal distribution of conditions favorable for late blight development (Table 3). In 2022, although the number of rainy days was highest (28 days), the number of days with high relative humidity (RH > 80%) during the critical infection period (June–July) was limited. Most high-humidity days occurred in August, when the crop had reached a more advanced developmental stage, reducing the potential for epidemic expansion.

In contrast, in 2023 and 2024, although total precipitation was lower, the distribution of favorable conditions was more closely aligned with key stages of crop development. A higher frequency of days with RH > 80% during June and July likely promoted earlier disease establishment and faster epidemic development in these years.

These results suggest that the temporal distribution of favorable infection conditions, rather than total seasonal precipitation alone, played a decisive role in determining the observed differences in disease severity among years.

This climatic pattern provides a mechanistic explanation for the disease progress dynamics described in the following section and supports the observed differences in cumulative disease intensity (AUDPC).

Table 3. Monthly distribution of rainy days (>1 mm) and days with high relative humidity (RH > 80%) during the growing seasons (2022–2024).

2022	Rain >1 mm (number of days)	RH>80% (number of days)
May	11	1
June	4	3
July	5	2
August	8	9
2023	Rain >1 mm (number of days)	RH>80% (number of days)
May	6	2
June	7	7
July	7	4
August	5	1
2024	Rain >1 mm (number of days)	RH>80% (number of days)
May	6	3
June	5	4
July	6	5
August	6	1

Note: Rainy days represent days with precipitation exceeding 1 mm. Days with RH > 80% indicate favorable conditions for infection and disease development of *Phytophthora infestans*.

3.2. Disease Progress during the Growing Season

The development of potato late blight was monitored through seven successive disease assessments performed during the growing season. The mean degree of attack (GA%) increased progressively as the crop developed, reflecting the typical temporal dynamics of late blight epidemics under field conditions (Figure 2).

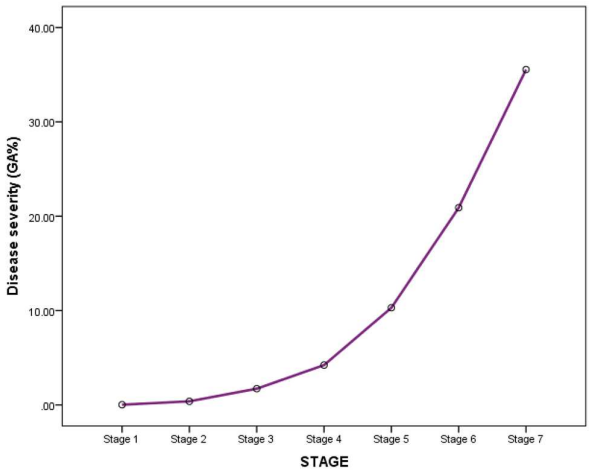


Figure 2. Disease progress of potato late blight expressed as mean degree of attack (GA%) during the seven assessment stages. GA (%) – degree of attack calculated based on disease frequency and intensity; values represent the mean of all experimental variants. The seven assessments correspond to successive growth stages during the growing season, corresponding to key phenological stages defined according to the BBCH scale.

Disease severity remained very low during the early stages of crop development, with mean GA values of 0.02% and 0.38% recorded at the first and second assessments, respectively. A gradual increase in disease intensity was observed during the vegetative growth phase, reaching 1.72% and 4.22% at the third and fourth evaluations.

A marked acceleration of disease development occurred during later growth stages, particularly during flowering and tuber bulking.

The mean GA value increased sharply to 10.29% in the fifth assessment and further to 20.89% in the sixth evaluation, reaching a maximum of 35.55% in the final assessment.

The disease progress curve (Figure 2) showed a characteristic sigmoidal pattern, with an initial latency phase, followed by a rapid exponential increase and a final saturation stage. This pattern is typical of polycyclic diseases such as late blight and reflects the increasing infection pressure under favorable environmental conditions.

These results provide a temporal framework for understanding disease dynamics and support the subsequent analysis of cumulative disease intensity expressed as AUDPC.

3.3. Effect of Experimental Factors on Disease Severity (AUDPC)

The analysis of disease severity based on AUDPC values revealed substantial variation among genotype × treatment combinations (Table 4). AUDPC values represent means calculated across the three experimental years (2022–2024).

Among the evaluated genotypes, Riviera exhibited the lowest AUDPC values under treatment B2 (205.88), indicating a favorable response to curative systemic treatments. Similarly, Darilena showed relatively low disease severity under preventive treatment scheme (B1), suggesting that early intervention was effective in limiting epidemic development for this genotype.

In contrast, higher AUDPC values were recorded under contact treatment (B4), particularly for Riviera (642.31) and Red Lady (640.89), indicating reduced effectiveness of this treatment strategy under high disease pressure. The untreated control (B5) also resulted in high AUDPC values, especially for Temerar (589.00), confirming the importance of fungicide application in limiting disease progression.

Table 4. Mean AUDPC values for genotype × treatment combinations, across three growing seasons (2022–2024)

Genotype	B1	B2	B3	B4	B5
Darilena	235.05	497.94	298.23	311.54	330.24
Red Lady	598.89	258.97	367.13	640.89	324.50
Riviera	394.66	205.88	299.27	642.31	224.81
Temerar	330.95	385.58	430.40	338.72	589.00

Note: B1 – preventive systemic treatment; B2 – curative systemic/systemic-contact treatment; B3 – systemic + contact treatment; B4 – contact treatment; B5 – untreated control.

The genotype × treatment interaction was statistically significant, indicating that the effectiveness of fungicide treatments varied depending on cultivar response.

The interaction plot (Figure 3) further highlights the differential response of genotypes to fungicide treatments. For instance, while some genotypes showed a substantial reduction in disease severity under systemic treatments (B1 and B2), others exhibited a more variable response pattern, emphasizing the role of genotype-specific tolerance mechanisms.

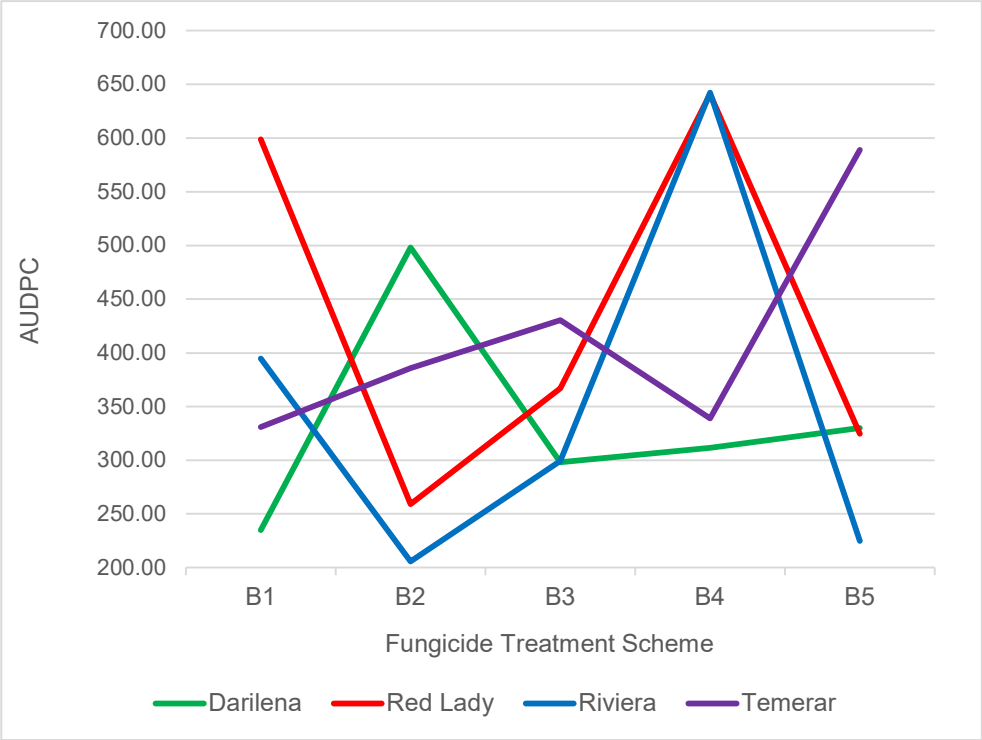


Figure 3. Interaction effect of potato genotype and fungicide treatment scheme on disease severity expressed as AUDPC. Values represent mean AUDPC across three growing seasons (2022–2024) for each genotype × treatment combination. Non-parallel trends indicate a significant genotype × treatment interaction.

3.4. Effect of Experimental Factors on Potato Yield

Potato yield showed considerable variation across years, genotypes, and fungicide treatment schemes. In 2022, yield ranged from 13.5 to 21.9 t ha^{-1}, while in 2023 and 2024 the range increased to 14.3–22.6 t ha^{-1} and 13.67–22.36 t ha^{-1}, respectively. In all years, the lowest yields were consistently recorded in the untreated control (B5), whereas the highest values were obtained under preventive (B1) and combined fungicide treatment schemes (B2–B3).

Across the three-year period, mean yield values ranged from 13.94 to 22.29 t ha^{-1} depending on genotype and treatment (Table 5; Figure 4). The highest yields were consistently recorded for the Temerar genotype under preventive treatment (B1), while the lowest values were observed in the untreated control.

Compared to the untreated control, fungicide treatments resulted in substantial yield increases, reaching up to approximately 65–70% under optimal conditions. These results indicate that effective disease management plays a crucial role in maintaining potato yield under late blight pressure.

Table 5. Potato yield (t ha^{-1}) as influenced by genotype and fungicide treatment schemes in the experimental years (2022–2024).

Genotype/year	Tuber yield (t ha^{-1})				
2022	**B1**	**B2**	**B3**	**B4**	**B5**
Darilena	19	17.5	18	16.9	13.5
Red Lady	20.1	19.9	18.4	17.8	17.7
Riviera	19.4	18.2	18.6	18	16.5

Temerar		21.9	19.1	20.8	19.6	17.9
	2023	**B1**	**B2**	**B3**	**B4**	**B5**
Darilena		19.8	18.4	18.9	17.7	14.3
Red Lady		20.9	20.7	19	18.7	18.5
Riviera		20.3	19.2	19.8	19	17.4
Temerar		22.6	20.2	21.8	20.6	18.8
	2024	**B1**	**B2**	**B3**	**B4**	**B5**
Darilena		19.48	17.18	18.17	16.57	14.02
Red Lady		20.58	19.34	18.26	17	15.18
Riviera		19.22	16.84	17.94	15.96	13.67
Temerar		22.36	18.96	20.41	19.1	15.63

Note: B1 – preventive systemic treatment; B2 – curative systemic treatment; B3 – systemic + contact treatment; B4 – contact treatment; B5 – untreated control.

To provide a general overview of treatment effects across experimental conditions, mean yield values averaged over the three growing seasons (2022–2024) are presented in Figure 4.

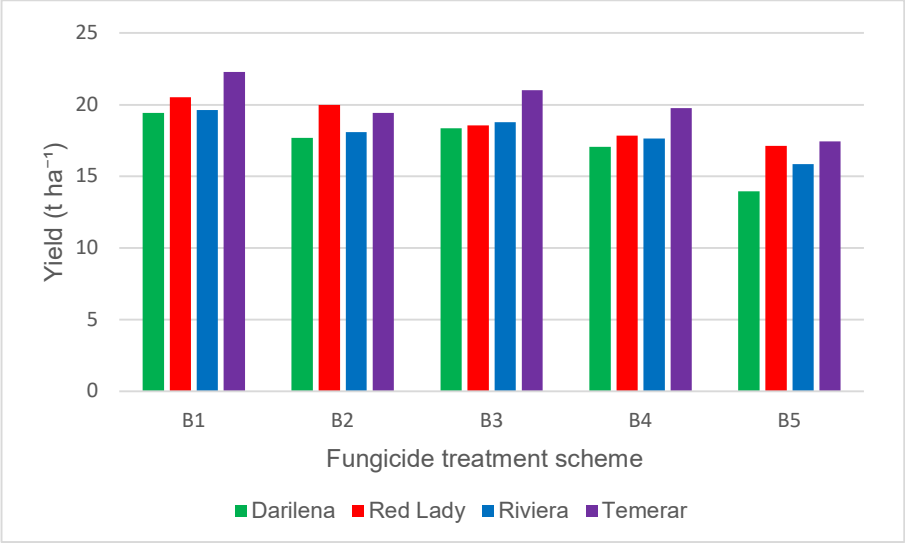


Figure 4. Effect of fungicide treatment schemes on potato yield for different genotypes. Values represent mean yield (t ha^{-1}) across three growing seasons (2022–2024).

Figure 4 illustrates that preventive and combined fungicide treatment schemes (B1–B3) consistently resulted in higher yields across all genotypes, whereas the untreated control (B5) showed the lowest productivity. Among the evaluated cultivars, Temerar exhibited the highest yield potential, while Darilena showed comparatively lower productivity under all fungicide treatment schemes.

The analysis of variance revealed that potato yield was significantly influenced by all the main experimental factors (Table 6). Highly significant effects were observed for year, treatment scheme, and genotype ($p < 0.001$), indicating that environmental conditions, crop protection strategies, and cultivar characteristics played a key role in determining crop productivity.

Table 6. Analysis of variance for potato yield as affected by year, genotype and treatment scheme.

Source of variation	df	F value	p value
Year	2	88.77	<0.001
Treatment	4	232.61	<0.001
Genotype	3	148.92	<0.001
Year × Treatment	8	6.13	<0.001
Year × Genotype	6	5.4	0.001
Treatment × Genotype	12	9.15	<0.001
Error	24	-	-

Note: df – degrees of freedom. *, **, *** indicate statistical significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

The strong effect of treatment (F = 232.61) highlights the critical role of fungicide application in sustaining yield under disease pressure. Genotype also had a highly significant effect (F = 148.92), reflecting differences in agronomic performance and disease tolerance among cultivars. The significant effect of year (F = 88.77) further confirms the influence of climatic variability on yield.

Significant interactions between experimental factors were also observed, including year × treatment, year × genotype, and treatment × genotype ($p < 0.001$). These interactions suggest that both treatment effectiveness and genotype performance varied depending on environmental conditions.

The relationship between disease severity and potato yield is presented in Figure 5.

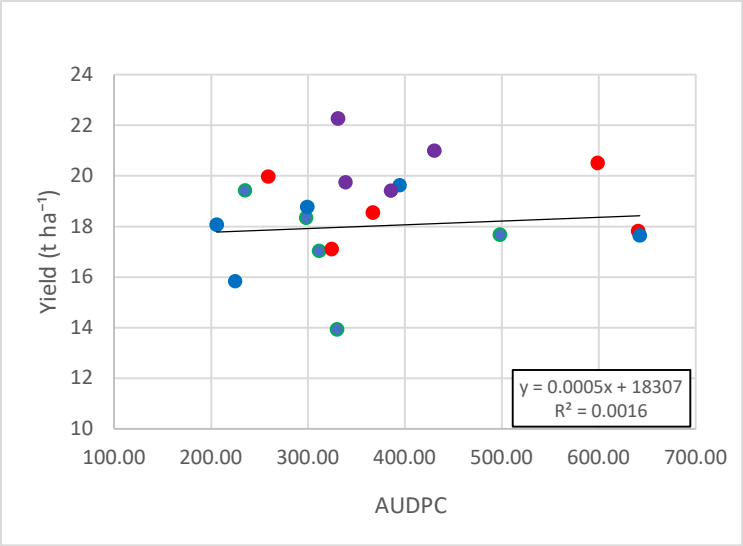


Figure 5. Relationship between potato late blight severity (AUDPC) and potato yield. Each point represents a genotype × treatment combination. The linear regression model indicates a weak relationship between disease severity and yield ($R^2 = 0.002$). Color coding: green - Darilena; red - Red Lady; blue - Riviera and violet – Temerar.

Regression analysis revealed a weak relationship between AUDPC and yield ($R^2 = 0.002$), indicating that disease severity did not account for yield variability. Yield was primarily determined by genotype performance and treatment strategy.

3.5. Tuber Size Distribution

The distribution of tuber size fractions showed moderate variation among years (Table 7). The highest yields for all size classes were recorded in 2023, while slightly lower values were observed in 2024. Medium-sized (35–55 mm) and large (>55 mm) tubers consistently represented the largest proportion of total yield, whereas small tubers (<35 mm) contributed less to overall productivity.

Table 7. Mean tuber yield (t ha^{-1}) by size fractions across years.

Year	<35 mm	35-55 mm	>55 mm
2022	4.73	6.85	6.87
2023	4.92	7.2	7.22
2024	4.60	6.57	6.61

Note: Values represent mean tuber yield for each size fraction calculated across all genotypes and fungicide treatment schemes.

The predominance of medium and large tubers suggests favorable growing conditions and effective crop management practices, as these size categories are generally associated with higher market value and better agronomic performance. The higher yields observed in 2023 are consistent with more favorable climatic conditions during that growing season, which supported tuber development and biomass accumulation.

The analysis of variance revealed that tuber size distribution was significantly influenced by all main experimental factors (Table 8). Highly significant effects ($p < 0.001$) were observed for year, treatment scheme, and genotype across all tuber size fractions.

Table 8. Analysis of variance for potato yield distribution among tuber size fractions.

Source of variation	df	<35 mm (F)	35–55 mm (F)	>55 mm (F)
Year	2	16.03***	97.46***	68.77***
Treatment	4	38.38***	344.69***	608.03***
Genotype	3	761.03***	513.18***	196.88***
Year × Treatment	8	2.77*	4.27**	4.69**
Year × Genotype	6	ns	7.05***	7.38***
Treatment × Genotype	12	135.55***	128.94***	96.35***
Error	24	–	–	–

Note: ns – not significant; *, **, *** indicate statistical significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

Genotype had a particularly strong influence on tuber size distribution, especially for the small (<35 mm) fraction ($F = 761.03$) and the medium-sized fraction (35–55 mm; $F = 513.18$), indicating substantial genetic differences in tuber formation and size allocation among the evaluated cultivars.

Treatment scheme also showed a pronounced effect, particularly for the large tuber fraction (>55 mm; $F = 608.03$), demonstrating that effective disease management not only increased total yield but also enhanced the proportion of commercially valuable tubers.

Significant genotype × treatment interactions were observed for all tuber size fractions, indicating that cultivar response to fungicide application differed in terms of tuber size formation. In addition, significant year-related interactions highlight the influence of climatic variability on tuber growth and size distribution.

Overall, these results indicate that both genetic characteristics and crop protection strategies play a decisive role in determining not only total yield but also the qualitative structure of potato production under field conditions.

4. Discussion

The results of this study highlight the complex interplay between environmental conditions, cultivar characteristics, and disease management strategies in determining potato crop performance under field conditions. These factors did not act independently but rather interacted to influence both disease development and yield outcomes.

Climatic conditions varied among experimental years and played a decisive role in disease dynamics. Although moderate temperatures combined with high humidity and rainfall are generally recognized as key drivers of *Phytophthora infestans* epidemics, the present study indicates that total seasonal precipitation alone was not a reliable predictor of disease severity. Despite the highest precipitation recorded in 2022, disease severity was lower than in 2023 and 2024. This finding suggests that the temporal distribution of favorable environmental conditions, particularly during critical growth stages (June–July), is more important than cumulative rainfall. Similar observations have been reported in previous studies emphasizing the importance of infection timing in epidemic development [5,6].

Disease progress followed a characteristic sigmoidal pattern, with low infection levels during early crop development and a rapid increase during flowering and tuber bulking stages. This behavior is consistent with the polycyclic nature of late blight and the increasing infection pressure associated with canopy closure and favorable microclimatic conditions [5,14].

The analysis of AUDPC values confirmed that both genotype and treatment scheme influenced disease severity. More importantly, the results highlight that treatment effectiveness was strongly genotype-dependent, highlighting the importance of considering cultivar-specific responses when designing disease control strategies. Similar studies have shown that cultivars with partial resistance tend to maintain lower AUDPC values under field conditions [7,18].

A key finding of this study is the weak relationship between disease severity and yield ($R^2 = 0.002$), indicating that yield variability was not directly driven by disease intensity alone. This result suggests that potato yield under field conditions is determined by a complex combination of factors, including genotype performance, treatment efficiency, and environmental conditions. In this context, reducing disease severity does not necessarily translate proportionally into yield gains. This finding adds important insight to previous studies [3], which emphasized the role of fungicide programs, by demonstrating that yield response cannot be explained solely by disease control.

The yield results further confirmed the strong influence of fungicide treatment schemes and genotypes. While effective fungicide programs significantly improved yield, genotypic differences played a major role in determining productivity and stability across years. Some cultivars exhibited lower disease severity, whereas others maintained higher yield potential under fungicide protection, indicating different adaptive strategies.

The analysis of tuber size distribution provided additional evidence that both disease management and genotype influence not only yield quantity but also its qualitative structure. The higher proportion of medium and large tubers under effective fungicide treatment schemes highlights the economic importance of integrated disease management strategies.

Overall, the findings of this study indicate that optimizing potato production under late blight pressure requires an integrated approach combining appropriate cultivar selection with well-timed fungicide applications. From a practical perspective, aligning fungicide treatments with critical crop growth stages and periods of high infection risk may improve both disease control efficiency and yield stability.

5. Conclusions

The results of this study highlight that potato late blight development and its impact on crop productivity are determined by the complex interaction between climatic conditions, genotype characteristics, and disease management strategies.

A key finding is that disease severity was not directly related to total seasonal precipitation, but rather to the temporal distribution of favorable environmental conditions during critical crop growth stages. This highlights the importance of infection timing in shaping epidemic development under field conditions.

The analysis of AUDPC confirmed that both genotype and fungicide treatment significantly influenced disease severity, with clear genotype-specific responses to treatment strategies. This suggests that disease management effectiveness depends not only on the applied fungicide scheme but also on cultivar characteristics.

A particularly important result of this study is the weak relationship between disease severity and yield (R^2 = 0.002), demonstrating that yield variability cannot be explained by disease intensity alone. Instead, yield was primarily determined by the combined effects of genotype performance, treatment efficiency, and environmental conditions.

In addition to total yield, disease management and genotype also influenced yield structure, with effective treatments increasing the proportion of medium and large tubers, which are of higher economic value.

From a practical perspective, the results suggest that optimizing fungicide application timing in relation to crop phenology and environmental conditions, together with the selection of suitable genotypes, can significantly improve both disease control and yield stability.

Overall, this study provides evidence that integrated management strategies, combining cultivar selection with well-timed fungicide applications, are essential for sustainable potato production under late blight pressure.

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