

Relationships between Sentinel-2 Vegetation Indices, Late Blight Severity, and Tuber Yield in Potato (*Solanum tuberosum* L.)

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ABSTRACT

Late blight caused by *Phytophthora infestans* remains one of the most destructive diseases affecting potato production worldwide. The present study evaluated the potential of Sentinel-2-derived vegetation indices for monitoring crop development, disease severity, and tuber yield in potato under field conditions.

Field experiments were conducted at the Agricultural Research and Development Station Suceava, Romania, during three consecutive growing seasons (2022-2024). Four potato cultivars (Darilena, Red Lady, Riviera, and Temerar) were evaluated. Crop health status was assessed through sequential disease evaluations, and disease progression was quantified using the area under the disease progress curve (AUDPC). Vegetation dynamics were monitored using Sentinel-2-derived NDVI, EVI, SAVI, and NDWI indices obtained through Google Earth Engine.

Vegetation indices showed considerable variation among years and cultivars, reflecting differences in climatic conditions and disease pressure. The highest NDVI values were recorded in 2022, while greater fluctuations were observed in 2024 under drier and warmer conditions. NDVI exhibited a significant positive correlation with tuber yield ($r=0.70^{**}$) and a moderate negative relationship with AUDPC (-0.39^{*}), confirming its sensitivity to changes in crop health status. Similar seasonal patterns were observed for EVI and SAVI, whereas NDWI provided complementary information regarding crop water status. Among the evaluated cultivars, Temerar and Riviera generally maintained higher vegetation index values and greater canopy persistence throughout the growing season.

The results demonstrate the usefulness of Sentinel-2 vegetation indices as reliable tools for monitoring potato crop development and late blight severity. Their integration into precision agriculture systems may improve disease assessment and support sustainable crop management strategies.

Keywords: potato, *Phytophthora infestans*, Sentinel-2, NDVI, vegetation indices, AUDPC, remote sensing, precision agriculture.

INTRODUCTION

Potato (*Solanum tuberosum* L.) is one of the most important food crops worldwide, ranking among the leading sources of carbohydrates for human consumption. Due to its high yield potential, nutritional value, and adaptability to diverse environmental conditions, potato plays a key role in global food security (Devaux et al., 2021; FAOSTAT, 2024). However, potato production is frequently constrained by biotic and abiotic stresses that significantly affect crop growth, tuber

quality, and yield (Duarte et al., 2019; Hatnean et al., 2025).

Among the diseases affecting potatoes, late blight caused by *Phytophthora infestans* (Mont.) de Bary, remains one of the most destructive pathogens worldwide. Under favorable environmental conditions, the disease can spread rapidly, causing severe defoliation and substantial yield losses (Fry et al., 2015; Schulz et al., 2019; Hermeziu, 2021). The increasing variability of climatic conditions has further complicated disease management, emphasizing the need for efficient monitoring tools capable of

providing timely information on crop health status (Hermeziu and Adam, 2024).

Traditional field assessments of disease severity are widely used but are often labor-intensive, time-consuming, and difficult to apply over large areas. In recent years, remote sensing technologies have emerged as valuable tools for monitoring crop development, physiological status, and disease progression (Zhang and Zhou, 2019; Chi et al., 2025).

The rapid development of smart agriculture and Agriculture 5.0 concepts has accelerated the adoption of Earth Observation technologies for crop monitoring. Freely available satellite data provided by the Copernicus Program, including Sentinel-1 radar and Sentinel-2 multispectral imagery, together with cloud-computing platforms and artificial intelligence algorithms, enable timely, large-scale assessment of crop status and support precision agriculture applications (Ivanovici et al., 2024, 2025). The availability of freely accessible Sentinel-2 imagery has considerably expanded opportunities for agricultural monitoring due to its high spatial and temporal resolution.

Vegetation indices derived from satellite imagery have been extensively used to assess crop vigor, biomass accumulation, photosynthetic activity, and plant stress. Among these indices, the Normalized Difference Vegetation Index (NDVI) is considered one of the most widely applied indicators of vegetation status (Rouse et al., 1974). Additional indices such as the Enhanced Vegetation Index (EVI), Soil Adjusted Vegetation Index (SAVI), and Normalized Difference Water Index (NDWI) provide complementary information regarding canopy structure, soil background effects, and plant water status (Gao, 1996; Huete et al., 2002). Previous studies have demonstrated the usefulness of these indices for detecting stress conditions, estimating crop productivity, and assessing disease-related changes in vegetation (Mahlein, 2016; Khanal et al., 2020).

Although remote sensing applications in potato production have increased considerably in recent years, information

regarding the relationships among vegetation indices, late blight severity, and tuber yield under Romanian environmental conditions remains scarce. Furthermore, comparative evaluations of different potato genotypes using Sentinel-2-derived vegetation indices are still scarce.

Therefore, the objective of this study was to evaluate the applicability of Sentinel-2-derived NDVI, EVI, SAVI, and NDWI indices for monitoring potato crop development and late blight severity in four potato genotypes cultivated under field conditions during three consecutive growing seasons (2022-2024). In addition, the relationships among vegetation indices, disease severity expressed through attack degree and AUDPC, and tuber yield were investigated to assess the potential of remote sensing techniques for supporting disease monitoring and crop management.

MATERIAL AND METHODS

Plant material

The biological material used in this study consisted of four potato (*Solanum tuberosum* L.) cultivars originating from Romanian and foreign breeding programs. The cultivars included Darilena, developed by the National Institute of Research and Development for Potato and Sugar Beet Braşov (Romania); Temerar, developed by the Agricultural Research and Development Station Suceava (Romania); Riviera, developed by Agrico Potatoes (The Netherlands); and Red Lady, developed by Solana Group (Germany).

Experimental conditions

The field experiment was conducted at the Agricultural Research and Development Station (ARDS) Suceava, Romania, during three consecutive growing seasons (2022-2024).

The experiment was set up using a randomized block design with three replications and included four potato cultivars. Each experimental plot consisted of one cultivar sown in 20 rows, each 8 m long, covering an area of 120 m² (120 m² × 4 cultivars = 480 m²; 480 m² × 3 replications = 1,440 m²). The tubers were planted with 75

cm between rows and 25 cm between plants within the row, resulting in a density of approximately 53,000 plants/ha⁻¹.

Weather conditions during the growing seasons were characterized by using monthly rainfall and mean air temperature data recorded at the experimental site.

All fungicide applications were performed uniformly across all experimental plots according to local potato production recommendations to ensure comparable crop protection conditions.

Disease assessment and epidemiological parameters

Late blight development caused by *Phytophthora infestans* (Mont.) de Bary was monitored through seven sequential assessments conducted during the growing season. The assessments corresponded to key phenological stages defined according to the BBCH scale and covered the main developmental phases of potato growth, from early leaf development to full flowering and tuber bulking.

At each assessment, 20 plants were randomly selected from each experimental plot (N=20) and examined for disease symptoms.

Disease incidence (F%) was calculated as the percentage of infected plants relative to the total number of evaluated plants:

$$F(\%) = (\text{Number of infected plants} / \text{Total number of evaluated plants}) \times 100$$

Disease intensity (I) was visually assessed using a 0-5 rating scale based on the proportion of affected foliage, according to Mohan and Thind (1999): 0 = no visible symptoms; 1 = 1-10% of the evaluated foliage affected; 2 = 11-25% affected; 3 = 26-50% affected; 4 = 51-75% affected; and 5 = >75% of the evaluated foliage affected.

The disease index (DI%) was calculated as:

$$DI(\%) = \frac{F \times I}{100}$$

where F represents disease incidence (%) and I represent disease intensity (%).

To quantify disease progression throughout the growing season, the Area Under the Disease Progress Curve (AUDPC) was calculated according to Campbell and Madden (1990):

$$AUDPC = \frac{\sum Y_i + Y_{i+1}}{2} \times (t_{i+1} - t_i)$$

$$AUDPC = \sum \left[\frac{Y_i + Y_{i+1}}{2} \right] \times (t_{i+1} - t_i)$$

where Y_i and Y_{i+1} represent the disease index (DI, %) recorded at two consecutive assessments, and $(t_{i+1} - t_i)$ represents the time interval, expressed in days, between the corresponding assessments. In the present study, AUDPC was calculated separately for each experimental plot using DI (%) values from the seven sequential disease assessments.

Sentinel-2 imagery and vegetation indices

Crop monitoring was performed using Sentinel-2 multispectral imagery provided through the Copernicus Program of the European Space Agency (ESA). Satellite data were accessed and processed using the Google Earth Engine (GEE) platform from the Harmonized Sentinel-2 MSI Level-2A surface reflectance dataset (COPERNICUS/S2_SR_HARMONIZED). Only images acquired between May and August, corresponding to the main potato growing period under the experimental conditions, and without significant cloud contamination over the experimental area were included in the analysis.

For the satellite-based analysis, each cultivar was represented within each replication by an aggregated spatial unit of approximately 120 m². Thus, 12 cultivar × replication spatial units (four cultivars × three replications) were evaluated for each Sentinel-2 acquisition (Figure 1).



Figure 1. Spatial delineation of the cultivar × replication experimental units (~120 m² each) used for Sentinel-2 data extraction in 2022

Prior to vegetation index calculation, Sentinel-2 band values were converted to surface reflectance by applying the dataset scale factor of 10,000. NDVI, EVI, SAVI, and NDWI were calculated to characterize crop canopy development and its response to biotic and abiotic stress. For each acquisition date, mean vegetation index values were extracted separately for each approximately 120 m² cultivar × replication polygon and exported as CSV files for subsequent statistical analysis and graphical representation.

Although the spatial units used for satellite data extraction units were approximately 120 m², their boundaries did not always align necessarily coincide with the Sentinel-2 pixel grid. Therefore, mixed-pixel and edge boundary effects could not be fully eliminated completely excluded, and the resulting satellite-derived vegetation indices were interpreted as spatially aggregated estimates of canopy status at the cultivar × replication level.

The following vegetation indices were calculated:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where GREEN corresponds to Sentinel-2 band B3 and NIR corresponds to band B8.

$$EVI = \frac{2.5 \times (NIR - RED)}{NIR + 6 \times RED - 7.5 \times BLUE + 1}$$

$$SAVI = \frac{(NIR - RED) \times (1 + L)}{NIR + RED + L}$$

where L = 0.5

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR}$$

These indices were used to characterize vegetation vigor, canopy development, and crop response to disease and environmental stress.

Tuber yield assessment

At harvest, tubers from each experimental plot were collected and weighed. Yield data were expressed on a plot basis and subsequently converted to t ha⁻¹. These measurements were used to evaluate the effects of genotypes, disease index, and environmental conditions on crop productivity.

Statistical analysis

Statistical analyses were performed using R software. Correlation matrices and heatmaps were generated using the corrplot and ggplot2 packages. Pearson correlation analysis was used to investigate relationships among vegetation indices, disease severity parameters, and tuber yield. Linear regression analysis was performed to assess the relationship between disease index and vegetation indices.

RESULTS AND DISCUSSION

Weather conditions during the experimental period

Weather conditions varied considerably among the three growing seasons (Table 1, Figure 2). The 2022 season recorded the highest cumulative rainfall during the potato growing period (213.5 mm), particularly in

August, while mean temperatures remained moderate (19.35°C). These conditions were

favorable for vegetative growth and canopy development.

Table 1. Weather conditions during the potato growing seasons (2022-2024)

Year	Total rainfall (May-August, mm)	Mean temperature (May-August, °C)
2022	213.5	19.35
2023	191.0	19.65
2024	107.6	20.95

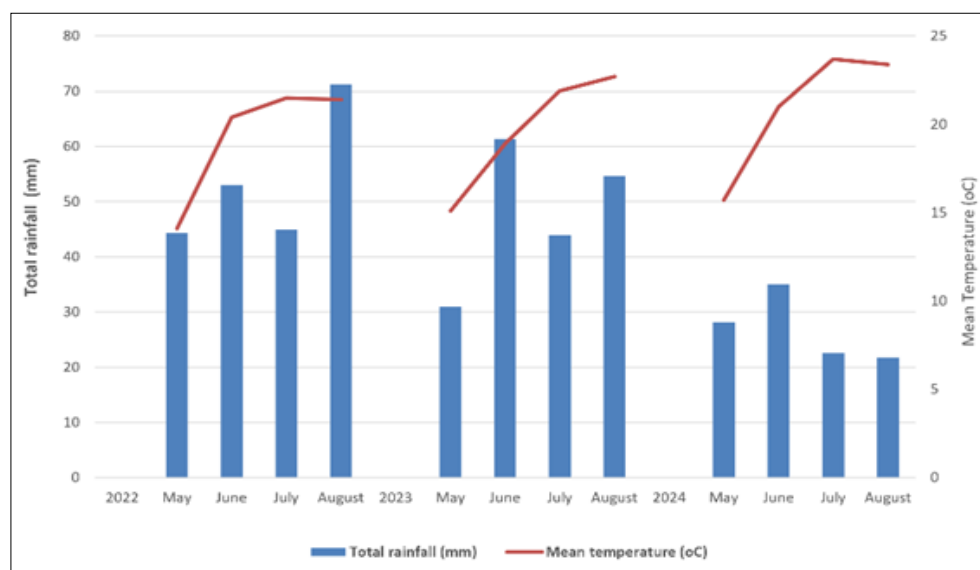


Figure 2. Monthly rainfall and mean air temperature recorded during the potato growing seasons (2022-2024)

In contrast, the 2023 season was characterized by a more balanced precipitation regime (191.0 mm) and similar average temperatures (19.65°C), providing relatively stable conditions for crop development.

The 2024 growing season was markedly drier, with total rainfall reaching only 107.6 mm, nearly half of that recorded in 2022. At the same time, mean temperatures were higher (20.95°C), especially during July and August. These conditions likely increased plant stress and contributed to the greater variability observed in vegetation indices during the growing season.

The drier and warmer conditions recorded in 2024 likely contributed to increased physiological stress and reduced canopy persistence.

The differences in rainfall distribution and temperature regime among years may explain part of the variation observed in late blight development, vegetation index dynamics, and crop performance.

Dynamics of NDVI values in the evaluated potato genotypes

NDVI values showed considerable variation among years and potato genotypes, reflecting the influence of environmental conditions and crop health status on canopy development (Figures 2-4).

The highest NDVI values were recorded in 2022, when maximum values ranged between 0.80 and 0.85 during the period of maximum canopy development. Similar NDVI dynamics have been reported in potato crops, where peak values coincided with maximum leaf area development and photosynthetic activity (Khanal et al., 2020; Campos et al., 2021). Thereafter, a progressive decline was observed from July onwards, indicating leaf senescence and a reduction in photosynthetically active biomass. Among the evaluated genotypes, Temerar consistently exhibited the highest NDVI values, whereas Darilena showed the lowest vegetation vigor (Figure 3).

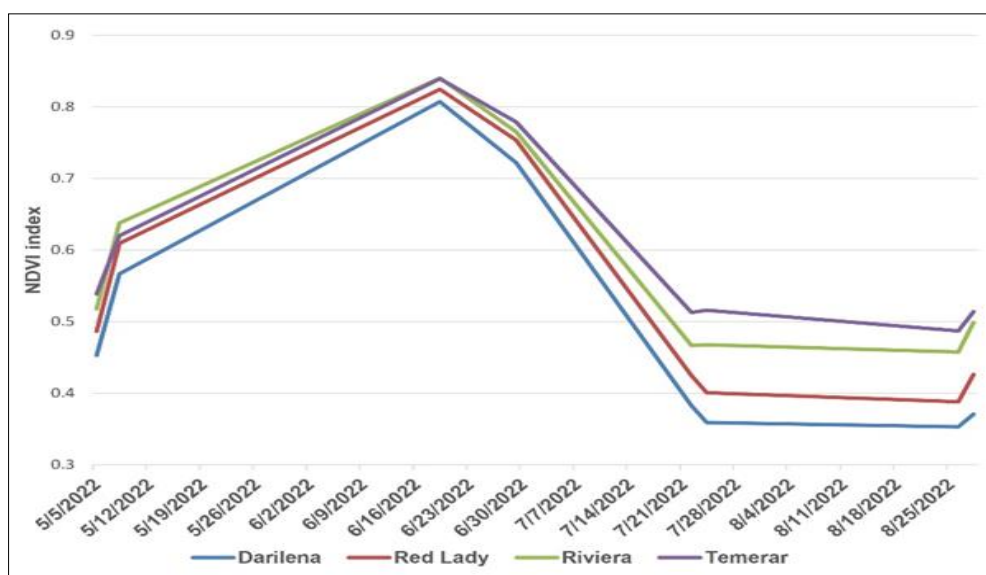


Figure 3. Dynamics of NDVI values depending on genotype in 2022

In 2023, NDVI values were lower but remained relatively stable throughout the second half of the growing season (Figure 4). This pattern may be associated with the more balanced climatic conditions recorded during

this year, as vegetation indices are strongly influenced by temperature and water availability (Clevers and Kooistra, 2012; Zhang and Zhou, 2019).

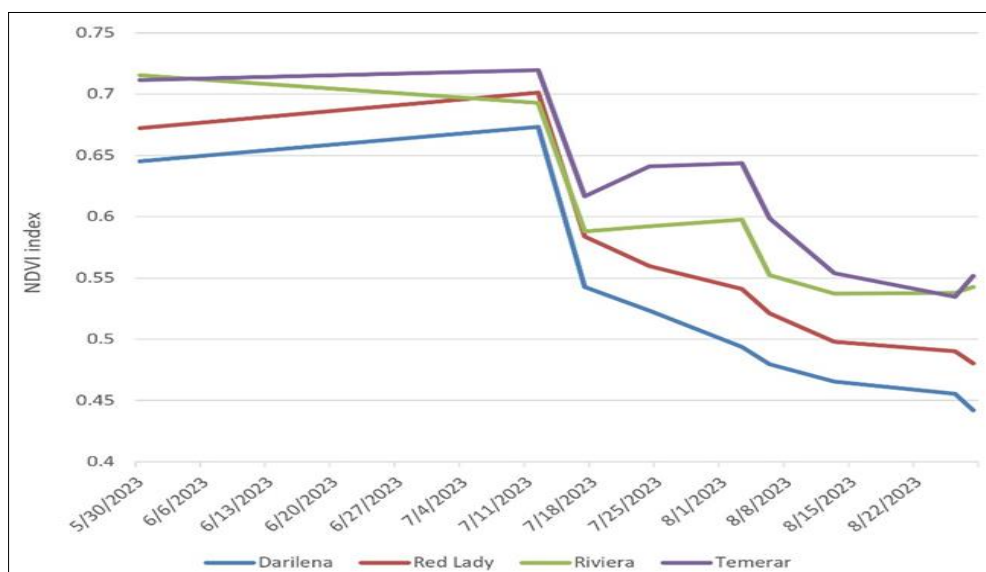


Figure 4. Dynamics of NDVI values depending on genotype in 2023

Of the evaluated cultivars Temerar exhibited the highest NDVI values among the evaluated genotypes, indicating sustained canopy activity.

The 2024 growing season was characterized by greater fluctuations in NDVI values and a lower overall vegetation response (Figure 5). The reduced rainfall and higher temperatures recorded during this season likely contributed to increased plant

stress and accelerated canopy decline. The higher NDVI values observed in Temerar and Riviera suggest a greater ability to maintain green leaf area under disease pressure, which may contribute to improved physiological resilience. Similar genotypic differences in canopy reflectance and vegetation index response have been reported in potato by León-Rueda et al. (2024).

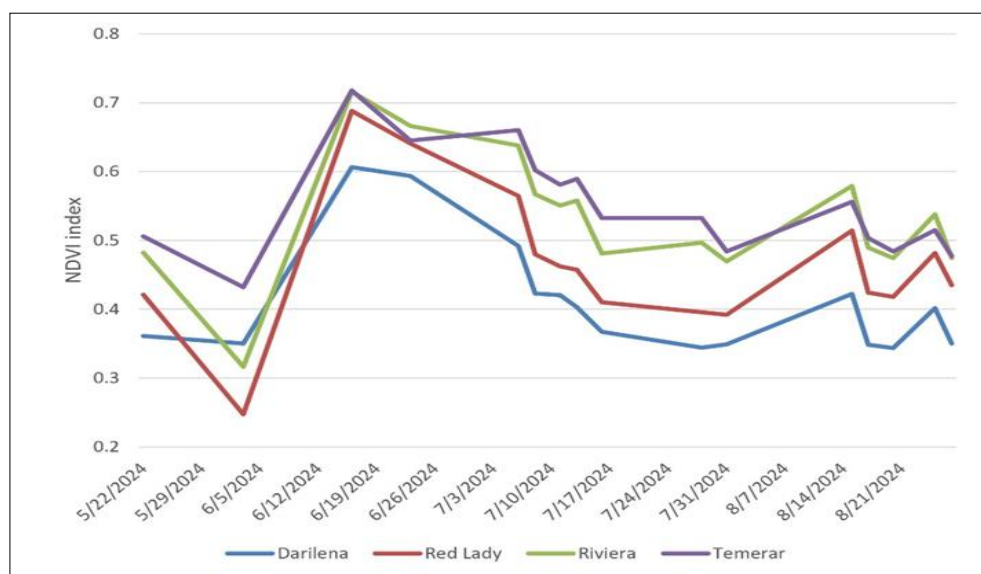


Figure 5. Dynamics of NDVI values depending on genotype in 2024

Across all growing seasons, NDVI increased progressively during the early stages of crop development, reaching maximum values during June and July, corresponding to peak canopy growth and photosynthetic activity. Subsequently, NDVI declined because of natural senescence and the combined effects of biotic and abiotic stress factors.

The observed differences among genotypes and years confirm the sensitivity of NDVI to environmental variability and highlight its usefulness for monitoring potato

crop development under field conditions, in agreement with previous studies that identified NDVI as a reliable indicator of crop vigor and physiological status (Tucker, 1979; Mahlein, 2016).

Comparative analysis of NDVI, EVI, and SAVI indices

The temporal dynamics of NDVI, EVI and SAVI closely followed the pattern observed for NDVI throughout the growing season (Figures 6-8).



Figure 6. Evolution of NDVI, EVI and SAVI indices during the vegetation period - 2022



Figure 7. Evolution of NDVI, EVI and SAVI indices during the vegetation period - 2023

All three vegetation indices increased during the period of active canopy development, reaching maximum values during June and July, and subsequently declined towards the end of the growing season because of leaf senescence and the effects of biotic and abiotic stress factors.

Similar seasonal trends have been reported for potato crops and other field crops, where vegetation indices closely reflect changes in canopy structure, leaf area, and photosynthetic activity (Huete et al., 2002; Khanal et al., 2020).

The most pronounced variations in vegetation

indices were observed in 2022, corresponding to favorable moisture conditions and vigorous canopy development (Figure 6). In contrast, the 2023 season exhibited more stable vegetation dynamics (Figure 7), while greater fluctuations were recorded in 2024 (Figure 8), likely due to reduced rainfall and higher temperatures during the growing period (Table 1). These findings are consistent with previous studies demonstrating the sensitivity of vegetation indices to environmental variability and crop stress (Zhang and Zhou, 2019; Campos et al., 2021).

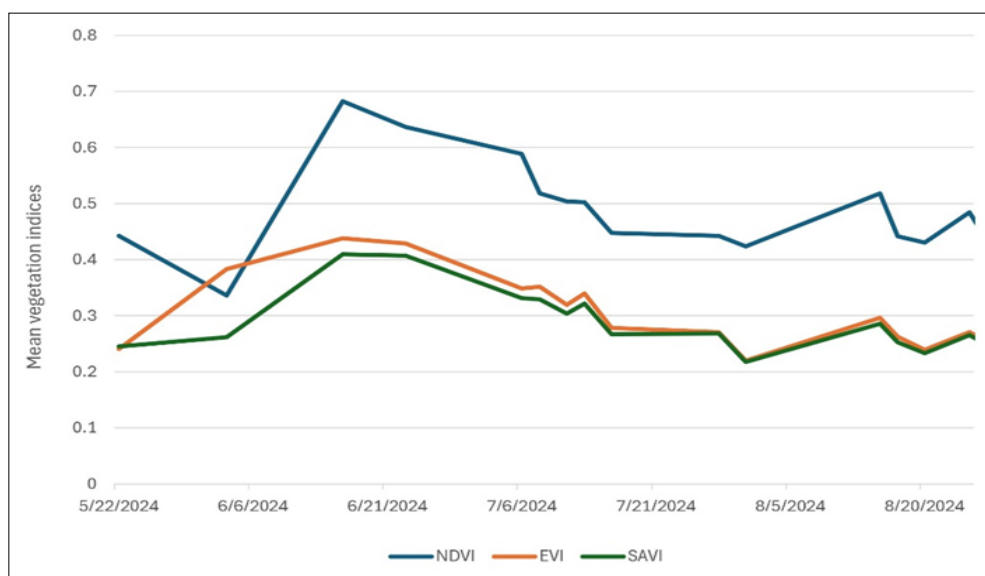


Figure 8. Evolution of NDVI, EVI and SAVI indices during the vegetation period - 2024

Analysis of NDWI index

Unlike NDVI, EVI and SAVI, the NDWI index displayed a distinct temporal pattern (Figure 9), reflecting variations in crop water status rather than vegetation vigor. Changes in NDWI values highlighted the influence of climatic conditions on canopy water content and confirmed the usefulness of this index for

detecting water-related stress in potato crops (Gao, 1996; Ceccato et al., 2002).

The most pronounced variations in NDWI index were observed in 2022, whereas 2023 showed a more stable vegetation trend. Marked fluctuations were also evident in 2024, likewise suggesting higher levels of climate stress.

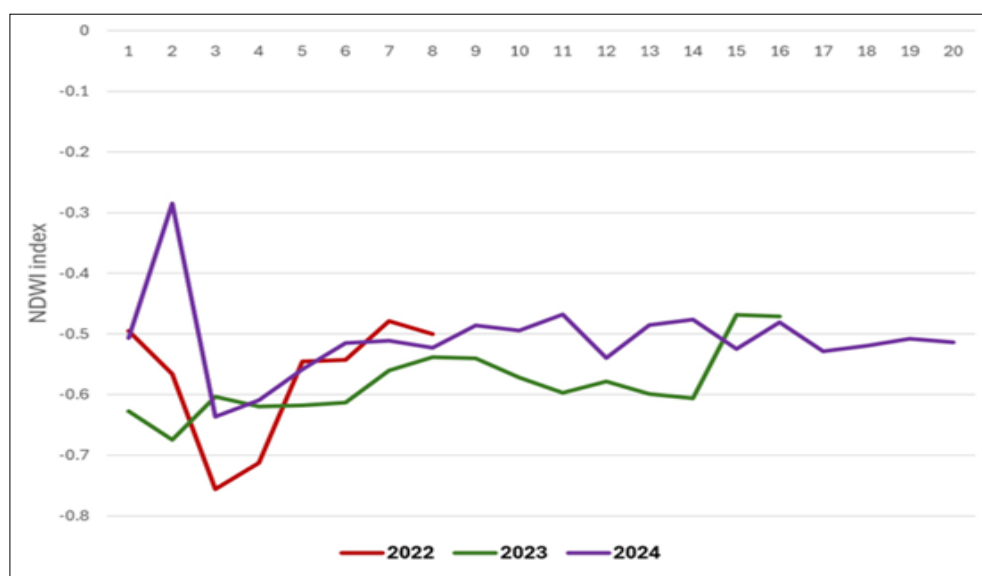


Figure 9. Evolution of NDWI index during the vegetation period - three years of experimentation (2022-2024)

Overall, the results demonstrate that Sentinel-2-derived vegetation indices provide complementary information on crop development, physiological status, and environmental stress, highlighting their potential as effective tools for monitoring potato crops and supporting disease assessment under field conditions.

Relationship between late blight severity and NDVI values

The relationship between DI and NDVI values revealed a consistent negative trend across all years of study, indicating a reduction in vegetation vigor with increasing disease index (Figure 10).

The strongest negative relationships were observed in 2022 and 2023, with Pearson correlation coefficients of $r=-0.878^{***}$ and $r=-0.826^{***}$, respectively. These results indicate that increasing disease index was associated with a substantial decline in canopy vigor and photosynthetic activity, as

reflected by lower NDVI values. Similar relationships between disease index and vegetation indices have been reported in potato and other crops, where foliar damage caused by pathogens reduces canopy reflectance in the near-infrared region and consequently lowers NDVI values (Mahlein, 2016; Khanal et al., 2020).

A negative relationship between DI and NDVI was also observed in 2024; however, the Pearson correlation was weaker ($r=-0.473^{*}$). This reduced association may be attributed to the stronger influence of climatic conditions, particularly the lower rainfall and higher temperatures recorded during the growing season, which likely affected crop development independently of disease severity.

The results confirm the usefulness of NDVI as an indirect indicator of crop health status and support its application as a rapid and non-destructive tool for monitoring late blight development under field conditions. Similar conclusions have been reported by

Zhang and Zhou (2019), who demonstrated the potential of remote sensing techniques for

detecting stress-induced changes in crop canopies.

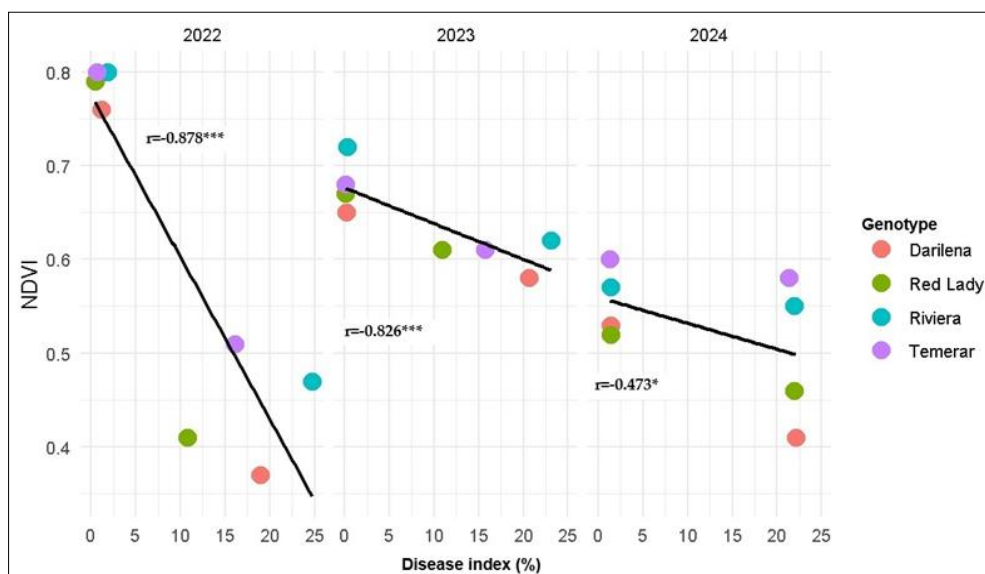


Figure 10. Linear regression between the DI and NDVI values for each genotype studied, during the trial period (2022-2024)

Relationships among AUDPC, NDVI and tuber yield

The correlation heatmap revealed important relationships among disease severity, vegetation status, and crop productivity (Figure 11).

A strong positive Pearson correlation was observed between NDVI and tuber yield ($r=0.70^{**}$), indicating that the maintenance of an active canopy and high vegetation vigor contributed to increased productivity. This

finding highlights the importance of preserving photosynthetically active leaf area throughout the growing season and confirms the usefulness of NDVI as an indicator of crop performance. Similar relationships between vegetation indices and potato yield have been reported in previous studies, where NDVI was shown to be closely associated with biomass accumulation and yield potential (Khanal et al., 2020; Campos et al., 2021).

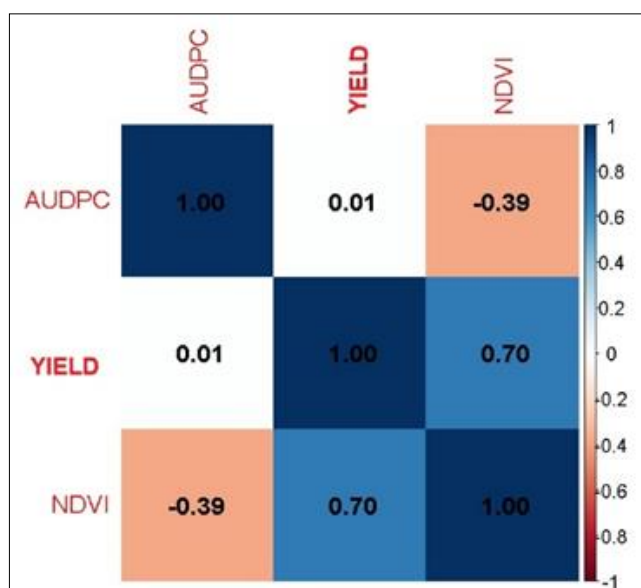


Figure 11. Heatmap of correlations between AUDPC, NDVI and tuber yield

A moderate negative Pearson correlation was found between AUDPC and NDVI ($r=-0.39^*$), suggesting that increasing disease severity was accompanied by a reduction in canopy vigor and photosynthetic activity. The decline in NDVI values with increasing AUDPC confirms the sensitivity of satellite-derived vegetation indices to disease-induced stress and supports their application in crop health monitoring (Mahlein, 2016; Zhang and Zhou, 2019).

In contrast, the relationship between AUDPC and tuber yield was negligible ($r=0.01$), indicating that yield performance was not determined solely by disease severity. This result suggests that genotype-specific characteristics, plant compensatory mechanisms, and environmental conditions also played an important role in determining final productivity. Similar observations have been reported in potato, where the impact of late blight on yield was influenced by cultivar tolerance and environmental variability (Fry et al., 2015; Haverkort et al., 2016).

Overall, the results demonstrate that NDVI represents a valuable complementary indicator for assessing crop performance and provide evidence of the complex interactions among disease development, canopy dynamics, and tuber yield in potato.

CONCLUSIONS

The present study demonstrated the usefulness of Sentinel-2-derived vegetation indices for monitoring potato crop development and assessing the impact of late blight under field conditions.

Although the study included only four potato cultivars, the consistency of the observed relationships across three growing seasons supports the applicability of Sentinel-2 vegetation indices for crop monitoring under field conditions.

Significant variations in NDVI, EVI, SAVI, and NDWI values were observed among years and genotypes, reflecting the influence of climatic conditions and crop health status on canopy dynamics.

Of the evaluated indices, NDVI proved to be the most informative indicator of vegetation

vigor, showing a strong positive correlation with tuber yield ($r=0.70^{**}$) and a significant negative relationship with Disease Index (DI). These results confirm its potential as a rapid and non-destructive tool for assessing crop performance and detecting disease-related stress.

The similar temporal patterns observed for NDVI, EVI, and SAVI indicate their reliability for monitoring canopy development, whereas NDWI provided complementary information regarding crop water status and environmental stress. The negative relationship between AUDPC and NDVI further demonstrated the sensitivity of satellite-derived vegetation indices to disease-induced changes in canopy structure and physiological activity.

Across the evaluated genotypes, Temerar and Riviera generally maintained higher vegetation index values (NDVI) throughout the growing season, indicating greater canopy persistence and improved adaptation to environmental stress conditions compared with Darilena and Red Lady.

Overall, the results highlight the potential of Sentinel-2 imagery and vegetation indices as effective tools for crop monitoring and precision agriculture applications. Their integration into disease surveillance programs may improve decision-making and contribute to more sustainable potato production systems under Romanian growing conditions.

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