

Original Research

Received 04 June 2026

Revised 22 July 2026

Accepted 06 Aug 2026

Natural Resources for Human Health 2026, Vol. 6 (15s): 540–547

KEYWORDS:

Potato viruses, latent infection, economic impact, ELISA, seed certification, *Solanum tuberosum*, Uzbekistan

Economic Impact and Eco-Physiological Management of Latent Potato Virus Infections in the Zarafshan Oasis, Uzbekistan

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ABSTRACT: Latent viral infections pose a hidden but economically devastating threat to seed potato systems, yet their true impact is often underestimated. This study quantified the prevalence of asymptomatic potato viruses across an altitudinal gradient and evaluated their physiological and economic consequences using ELISA diagnostics.

Field experiments were conducted at 750, 1000, and 1200 m a.s.l. with four cultivars. Visual scoring and DAS-ELISA were applied to detect PVX, PVS, PVM, PVY, and PLRV. Yield penalties, deterioration of tuber quality, and economic losses were modelled.

Latent infections affected 36.4–92.0% of plants, with PVY predominating (61.4% in lowlands). Mixed infections reduced marketable yield by >40%. Economic modelling revealed that undetected latent infections could reduce net revenue by up to 34.5% per hectare. ELISA-based screening proved cost-effective, with a benefit-cost ratio of 1:4.7.

Routine post-harvest ELISA screening combined with high-altitude seed multiplication offers an economically viable strategy for sustainable seed potato production

1. INTRODUCTION

Potato (*Solanum tuberosum* L.) is a critical food security crop in Uzbekistan, yet its production is increasingly threatened by viral degeneration. The Zarafshan oasis, one of the country's major agricultural regions, contributes significantly to national potato production, providing approximately 17% of Uzbekistan's potato and vegetable output [1]. However, the region's intensive agricultural practices, including monocropping and heavy use of mineral fertilizers, have exacerbated soil degradation and created favourable conditions for the spread of viral pathogens [1]. Among the various constraints, latent (asymptomatic) viral infections represent the most insidious challenge because they remain undetected during routine field inspections, allowing infected seed tubers to perpetuate degeneration across generations.

Globally, it is estimated that viral diseases cause 10–40% yield losses in potato, with economic damages exceeding USD 1 billion annually [2]. In Uzbekistan, the situation is particularly acute. Research conducted in the Samarkand region has revealed alarmingly high infection rates: DAS-ELISA testing identified Potato Virus Y (PVY) in up to 96.3% of tested fields, followed by Potato Leaf Roll Virus (PLRV) at 68.3%, and Potato Virus M (PVM) at 52.3%. These rates are significantly higher than those observed in the Tashkent region, where PVS predominated at 64.7% [3]. Such regional disparities highlight the influence

of local ecological conditions, vector populations, and agronomic practices on viral epidemiology. Research results emphasized the importance of virus-free primary seed production for Zarafshan potato varieties as a foundational strategy for managing viral diseases in the region [4].

The climatic conditions of the Zarafshan oasis play a decisive role in shaping viral disease dynamics. The region is characterized by a harsh continental climate with high summer temperatures, which accelerate the population growth and flight activity of aphid vectors (Aphididae), thereby facilitating the rapid spread of non-persistent viruses such as PVY [1]. Research results have demonstrated that elevated temperatures exacerbate physiological degeneration in potato plants, reducing chlorophyll content in leaves, suppressing photosynthesis and transpiration, and ultimately decreasing yield and disease resistance. Furthermore, high temperatures have been shown to promote the expression of latent viral infections, making symptom expression more pronounced under heat stress conditions [5].

The altitudinal gradient across the Zarafshan oasis offers a natural experimental framework for studying virus-vector-environment interactions. Lowland areas (approximately 750 m a.s.l.) experience higher temperatures and greater vector pressure, while highland zones (above 1000 m a.s.l.) provide cooler microclimates that naturally suppress aphid populations. Earlier research in the Zarafshan Valley identified several potato cultivars, including Quvonch-1656M, Bahro-30, and Hamkor-1150, that exhibit relative resistance to viruses X, S, M, and Y, as well as tolerance to heat and drought stress [6]. These findings underscore the potential for integrating cultivar selection with altitudinal zoning as a disease management strategy. Research results further highlighted the necessity of combining varietal resistance with systematic virus testing to achieve sustainable seed production [4]. The epidemiology of potato viruses is strongly influenced by environmental gradients, particularly altitude and temperature. Lowland areas with warm climates favour aphid vector populations, accelerating the spread of non-persistent viruses such as Potato Virus Y (PVY) [5]. Conversely, high-altitude zones (>1000 m) naturally suppress vector activity, making them ideal for seed multiplication [7]. However, even in highland areas, latent infections persist, creating a false sense of security among farmers and certifying agencies. Authors results noted that symptom expression is suppressed under cool conditions, yet viral titres remain high enough to cause significant yield penalties [8].

The physiological mechanisms underlying latent virus-induced yield losses are multifaceted. Viral infections disrupt photosynthetic efficiency, carbohydrate metabolism, and phytohormonal balance, ultimately reducing tuber size and quality [9]. Importantly, these physiological disruptions often occur in the absence of visible symptoms, making them difficult to detect without serological tools. ELISA has been validated as a highly sensitive and specific diagnostic method, capable of detecting virus titres as low as 10–100 ng/mL in plant sap [10]. Despite its proven efficacy, ELISA adoption in Uzbekistan remains limited, primarily due to cost constraints and lack of infrastructure. Recent studies have emphasized the importance of integrating serological diagnostics into seed certification programmes, particularly in regions with high viral pressure such as the Zarafshan oasis [3–4].

A critical knowledge gap exists regarding the economic feasibility of routine ELISA screening in low-resource settings. While authors demonstrated the technical superiority of ELISA over visual inspection, few studies have performed economic cost-benefit analyses specific to Central Asian agroecosystems [11]. Similarly, the interaction between cultivar genotype and latent virus stress has received scant attention in this region, despite evidence from Europe and the Americas showing significant genotype-specific responses [12]. Furthermore, the potential composting of local agricultural waste offers complementary avenues for improving soil health and crop resilience in the region [13]. Previous studies had already advocated for integrated approaches combining seed health, varietal selection, and environmental management [4].

Therefore, this study was conducted with the following novel objectives:

- (i) to quantify the prevalence and altitudinal distribution of latent potato viruses in the Zarafshan oasis;
- (ii) to evaluate the physiological and economic impacts of latent infections on tuber yield and quality;
- (iii) to assess the cost-effectiveness of routine ELISA-based screening relative to visual inspection alone; and
- (iv) to develop an evidence-based, economically viable seed certification protocol tailored to Uzbekistan's conditions.

2. MATERIALS AND METHODS

2.1 Study and Plant Material

Field experiments were conducted during the spring season (March–June) across three altitudinal zones in the Zarafshan oasis:

- Lowland plain: 750 m a.s.l. (Samarkand district)
- Foothill: 1000 m a.s.l. (Jomboy district)
- Mountainous: 1200 m a.s.l. (Urgut district)

Four locally registered cultivars – Sante, Quvonch-1656M, Bakhro-30, and Hamkor-1150 – were selected based on their contrasting genetic backgrounds and economic importance. These cultivars have been previously identified as promising for the Zarafshan Valley conditions, with Bakhro-30 officially included in the State Register of the Republic of Uzbekistan (Mukhammadiev et al., 2023). Plots (10 m² each) were arranged in a randomized complete block design with three replications. Standard agronomic practices were uniformly applied [15].

2.2 Virus Diagnostics

Visual scoring was performed at flowering and maturity using a 0–5 severity scale. Leaf samples (upper, middle, and lower canopy) were collected from 50 plants per plot. DAS-ELISA was performed using polyclonal antibodies for PVX, PVS, PVM, PVY, and PLRV [10]. Absorbance at 405 nm was recorded, with positive thresholds set at twice the healthy control mean. Additionally, indicator plant methods were employed for confirmation of PVY symptoms, using *Nicotiana tabacum* and *Datura metel* as sensitive bioassay hosts [14].

2.3 Physiological Parameters

At harvest, 20 plants per plot were assessed for: total tuber weight per plant (g), number of tubers per hill, average tuber weight (g), tuber size distribution (marketable >45 mm; unmarketable <45 mm), dry matter content (%).

2.4 Economic Analysis

Net revenue per hectare was calculated using prevailing market prices (USD/kg) and production costs (USD/ha). Three scenarios were modelled: Scenario A: No screening (visual inspection only), Scenario B: Visual + ELISA screening for highland seed plots, Scenario C: Visual + ELISA screening for all plots. Benefit-cost ratios (BCR) were calculated as: $BCR = (\text{Revenue from screened crop} - \text{Revenue from unscreened crop}) / \text{Screening cost}$.

2.5 Statistical Analysis

Data were analysed using analysis of variance (ANOVA) to determine the significance of treatment effects, with mean separations performed using Fisher's Least Significant Difference (LSD) test at a significance level of $p \leq 0.05$. All statistical evaluations were processed using Microsoft Excel.

3. RESULTS AND DISCUSSION

3.1 Prevalence and Altitudinal Distribution of Latent Viruses

ELISA revealed widespread latent infections across all zones, with total infection rates ranging from 36.4% (highland) to 92.0% (lowland). PVY was the most prevalent virus, infecting 61.4% of lowland seed lots, but dropping to 36.4% at 1200 m. This altitudinal gradient is consistent with previous reports from the Samarkand region, where PVY incidence reached 96.3% in some lowland districts [3]. Mixed infections (PVX+PVS+PVM+PVY) occurred in 20.8% of foothill samples and 11.1% of highland samples. A significant negative correlation was found between altitude and total latent infection rate ($r = -0.89$, $p < 0.01$).

Interestingly, contact-transmitted viruses (PVX, PVS, and PVM) showed no significant altitudinal variation ($p > 0.05$), confirming their mechanical transmission pathways, independent of vector activity. This implies that even high-altitude seed plots remain vulnerable to these pathogens unless strict sanitation and certified seed sources are used. These findings align with earlier monitoring data showing that PVX and PVS are more prevalent in regions where tuber cutting is common practice (Monitoring results, 2007-2009).

3.2 Physiological and Yield Penalties

Latent viral infections inflicted significant yield losses, even in asymptomatic plants. Single PVY infections decreased total yield by 14.0–39.0%, while mixed infections caused reductions exceeding 40% (Table 1). The physiological mechanisms driving these yield penalties varied by cultivar: Quvonch-1656M and Sante exhibited reductions in both tuber count and size. Bakhro-30 and Hamkor-1150 showed an increase in tuber number (reflecting a compensatory response), accompanied by a 25.1–38.1% decrease in tuber weight, ultimately leading to smaller, unmarketable tubers. Table 1 summarizes the physiological parameters affected by latent PVY infection under lowland conditions.

Table 1. Physiological responses of potato cultivars to latent PVY infection under lowland conditions (750 m a.s.l.)

Cultivar	Healthy Yield (g/plant)	PVY Yield (g/plant)	Healthy Tuber Count	PVY Tuber Count	Healthy Avg. Wt (g)	PVY Avg. Wt (g)	Unmarketable Tubers (%)	Yield Reduction (%)
Quvonch-1656M	465	340	7.5	6.1	62.3	55.7	18.7	27.0
Bakhro-30	540	419	7.7	8.0	70.0	52.4	25.1	22.4
Hamkor-1150	610	450	6.8	8.1	89.7	55.5	38.1	18.1
Sante	450	351	7.0	5.6	64.2	62.7	16.3	22.0
LSD_{0.05}	21.7–33.0	–	–	–	–	–	–	–

Significantly the increase in unmarketable tubers (small <45 mm) was most pronounced in Hamkor-1150 (38.1%) and Bakhro-30 (25.1%), indicating that latent PVY infection directly compromises tuber quality, not just quantity. This is economically significant because unmarketable tubers fetch 40–50% lower prices, further reducing net revenue.

3.3 Economic Feasibility of ELISA Screening

The economic modelling performed in this study revealed substantial differences in net revenue and overall profitability across the three screening scenarios evaluated (Table 2). These scenarios were designed to reflect realistic seed certification options, ranging from a minimal-cost approach relying solely on visual inspection to a comprehensive strategy incorporating serological testing for all production plots.

Table 2. Economic comparison of screening scenarios for seed potato certification (in UZS)

Scenario	Screening Cost (UZS/ha)	Marketable Yield (t/ha)	Net Revenue (UZS/ha)	Benefit-Cost Ratio (BCR)
A: Visual only	–	18.2	58,240,000	–
B: Visual + ELISA (highland only)	5,376,000	24.5	78,400,000	3.8
C: Visual + ELISA (all plots)	10,752,000	28.0	89,600,000	4.7

Scenario A, which relied exclusively on visual field inspections without any serological confirmation, resulted in the lowest marketable yield (18.2 t ha⁻¹) and net revenue (UZS 58,240,000 ha⁻¹). Although this approach incurs no direct diagnostic costs, the substantial yield penalties associated with undetected latent viral infections—particularly PVY and mixed complexes—severely compromise economic returns. Visual inspection alone failed to identify asymptomatic infections, which were prevalent

across all altitudinal zones, thereby allowing infected seed tubers to perpetuate degeneration and reduce both tuber quantity and quality.

In Scenario B, ELISA screening was implemented exclusively for highland seed production plots (>1000 m a.s.l.), where vector pressure is naturally lower. This targeted approach incurred a screening cost of UZS 5,376,000 ha^{-1} but increased marketable yield to 24.5 t ha^{-1} , generating a net revenue of UZS 78,400,000 ha^{-1} . The benefit-cost ratio (BCR) for this scenario was 3.8, indicating that every UZS 1 invested in ELISA testing for highland plots returned UZS 3.8 in additional revenue. While this scenario represents a significant improvement over visual inspection alone, it does not address the risk of latent infections in lowland areas, where PVY prevalence is highest and mixed infections cause the most severe yield losses.

Scenario C, which involved universal ELISA screening for all production plots regardless of altitude, proved to be the most economically advantageous. Although this approach required the highest screening cost (UZS 10,752,000 ha^{-1}), it yielded the greatest marketable output (28.0 t ha^{-1}) and the highest net revenue (UZS 89,600,000 ha^{-1}). The benefit-cost ratio for universal screening was 4.7, meaning that every UZS 1 invested in ELISA testing generated UZS 4.7 in additional revenue compared to Scenario A. The incremental gain in net revenue from Scenario A to Scenario C amounted to UZS 31,360,000 ha^{-1} , far exceeding the additional screening cost of UZS 10,752,000 ha^{-1} .

Importantly, the economic superiority of Scenario C is attributable not only to increased tuber yield but also to improved tuber quality. Universal ELISA screening enabled the early detection and removal of virus-infected seed lots, thereby reducing the proportion of unmarketable small tubers (<45 mm) and increasing the share of marketable produce. As demonstrated in Table 1, latent PVY infection increased unmarketable tuber proportions by up to 38.1% in susceptible cultivars such as Hamkor-1150. By preventing the propagation of such infected material, ELISA screening directly enhances both the quantity and quality of harvested produce, translating into higher farm-gate prices and improved profitability.

Furthermore, the positive BCR values obtained for both targeted (3.8) and universal (4.7) ELISA screening provide strong empirical evidence that investment in serological diagnostic infrastructure is not only technically effective but also economically justified. These findings are particularly relevant for Uzbekistan's seed certification authorities, as they demonstrate that the initial costs of establishing ELISA laboratories, training personnel, and conducting routine testing are outweighed by substantial long-term gains in yield, quality, and revenue.

From a policy perspective, the results suggest that a tiered implementation strategy could be adopted, beginning with ELISA screening for highland nuclear seed plots (Scenario B) and progressively expanding to universal coverage (Scenario C) as diagnostic capacity and resources permit. Such a phased approach would allow for cost-effective scaling of serological diagnostics while maximizing economic returns and ensuring the sustainability of the national seed potato production system.

In conclusion, the economic analysis unequivocally supports the integration of ELISA screening into Uzbekistan's seed certification framework. The substantial yield gains, quality improvements, and favourable benefit-cost ratios observed in this study provide a robust financial rationale for prioritizing investment in diagnostic infrastructure and routine serological testing. These measures, combined with altitudinal zoning and cultivar-specific management, form the cornerstone of a sustainable and economically viable seed potato industry in the Zarafshan oasis and beyond

3.4 Discussion

The high prevalence of latent viral infections (36.4–92.0%) across all altitudinal zones underscores the inadequacy of visual inspection as a sole diagnostic tool. This finding is consistent with global reports by Kreuze et al. (2020) and Jones (2021), but our study goes further by quantifying the economic dimension of this threat. The fact that visibly healthy plants can harbour virus titres sufficient to reduce yield by 27% (Quvonch-1656M) or increase unmarketable tubers by 38% (Hamkor-1150) has profound implications for seed certification and farmer livelihoods. The particularly high PVY prevalence in Samarkand region (96.3%) reported in earlier monitoring studies [3] further emphasizes the urgent need for systematic diagnostic interventions, as advocated by research results [4].

The pronounced altitudinal gradient in PVY incidence—a 4.5-fold reduction at 1200 m—confirms the effectiveness of high-altitude zones as natural barriers against vector-borne viruses. This aligns with the findings of Karasev and Gray (2013) and Lacomme et al. (2017), as well as the regional observations of Nazarov et al. (n.d.) regarding the geoeological stabilization potential of the Zarafshan oasis. However, the persistence of contact-transmitted viruses (PVX, PVS, PVM) across all altitudes,

as also observed in monitoring studies across Samarkand districts (Monitoring results, 2007-2009), indicates that highland isolation alone is insufficient. The absence of significant altitudinal variation for these viruses suggests that mechanical transmission through contaminated seed tubers and farming equipment remains a critical pathway. In the Zarafshan oasis, where tuber cutting is a common practice, this mechanical transmission route poses a significant challenge (Ergashev et al., 1989).

The exacerbating role of high temperatures in viral disease expression, as documented by Maxmudova (2025), is particularly relevant for the Zarafshan oasis. Climate projections for Central Asia indicate increasing temperatures, which could further accelerate aphid population growth and extend transmission windows for viruses like PVY. This underscores the importance of adaptive management strategies, including the selection of heat-tolerant cultivars and the optimization of planting dates to avoid peak vector activity periods. Ergashev et al. (1989) had already recognized the importance of ecological adaptation in seed production strategies.

The differential responses among cultivars highlight the potential for genotype-based management. Cultivars like Bakhro-30 and Hamkor-1150, which are already recognized for their relative resistance to viruses X, S, M, and Y under Zarafshan Valley conditions (Inagamova et al., n.d.), show promise for lowland cultivation where vector pressure is high. However, the quality penalty (increased unmarketable tubers) observed in these cultivars under PVY stress suggests that resistance to infection does not necessarily confer tolerance to yield and quality penalties. Breeding programmes should therefore select for both infection resistance and physiological tolerance, including stable tuber size under viral stress.

Beyond seed certification, holistic approaches to soil health and crop resilience are essential. As reported by Pardaev et al. (2026), the use of organic amendments such as cattle manure and wheat straw can increase soil organic matter, improve water retention, and support beneficial microbial activity, thereby reducing plant stress and mitigating the impacts of viral infections. Composting can improve soil organic matter content, enhance water-holding capacity, and support beneficial microbial communities, thereby reducing plant stress and potentially mitigating the impacts of viral infections. Integrating composting practices with certified seed production could offer a synergistic approach to sustainable potato cultivation in the Zarafshan oasis. This aligns with the earlier recommendations for integrated virus management [4].

The economic analysis confirms that ELISA screening is both technically effective and financially viable. Universal screening (Scenario C) yielded a benefit-cost ratio of 4.7, indicating that every UZS 1 invested returns UZS 4.7 in additional revenue through increased marketable yield and improved tuber quality. This aligns with European certification reports [11], where routine ELISA testing consistently generates positive returns by reducing viral degeneration and extending seed lot longevity.

The yield gap between visual inspection alone (18.2 t ha⁻¹) and universal ELISA screening (28.0 t ha⁻¹) highlights the substantial economic cost of undetected latent infections, particularly in lowland areas where PVY prevalence reaches 61.4%. The positive BCR of 3.8 for highland-only screening further supports a phased implementation strategy, beginning with nuclear seed plots and gradually expanding diagnostic capacity.

From a policy perspective, the relatively modest screening cost (UZS 10,752,000 ha⁻¹) compared to net revenue gains (UZS 31,360,000 ha⁻¹) justifies prioritising investment in ELISA laboratories, personnel training, and routine post-harvest testing. This aligns with earlier recommendations for integrated virus management [4], combining seed health, varietal resistance, and environmental optimisation.

4. CONCLUSION

Based on the comprehensive analysis of experimental data, field observations, serological diagnostics, and economic modelling, the following scientifically grounded conclusions have been drawn.

- Latent viral infections are widespread (36.4–92.0%) and economically devastating in the Zarafshan oasis, with PVY predominating in lowlands and mixed infections causing >40% yield losses.
- Altitudinal zoning effectively suppresses PVY (4.5-fold reduction at 1200 m) but does not eliminate contact-transmitted viruses, necessitating complementary sanitation measures.
- Climate change exacerbates viral threats, with high temperatures accelerating vector activity and symptom expression.

- Cultivar-specific responses require tailored management: tolerant cultivars may still suffer quality penalties, reducing marketable tuber proportion by up to 38.1%.
- ELISA screening is economically viable, with a benefit-cost ratio of 4.7, justifying investment in diagnostic infrastructure and routine testing.
- A tiered certification protocol combining highland isolation, mandatory ELISA screening, genotype-specific recommendations, and integrated soil health practices is recommended for sustainable seed potato production in Uzbekistan.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the technical and logistical support provided by the Institute of Agrobiotechnologies and Food Security at Samarkand State University after named Sharof Rashidov. We also express our sincere appreciation to the anonymous reviewers for their valuable feedback and constructive suggestions, which significantly improved the quality of this manuscript.

AUTHOR CONTRIBUTIONS

Author Contributions

Davlat Normuradov: Original writing, Conceptualization, Methodology, Funding acquisition. **Mamadiyar Khayitov:** Supervision, Project administration, Resources. **Bakhrom Khalmirzaev:** Investigation, Field experiments, Data Curation. **Safar Sadinov:** Formal analysis, Software, Visualization. **Rustam Rakhimov:** Methodology, Laboratory analysis (ELISA diagnostics). **Oybek Sulaymonov:** Investigation, Sample collection. **Feruz Oblakulov:** Resources, Validation, Coordination of field trials. **Javokhir Ergashev:** Data Curation, Writing – Original Draft. **Gafur Obruev:** Writing – Review & Editing, Supervision.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

This study did not involve human participants, vertebrate animals, or endangered plant species. Therefore, ethical approval was not required.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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