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RESEARCH ARTICLE
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Application of Electro- and Magnetic Therapy for Elimination of Potato Viruses

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ABSTRACT

This study investigates the effectiveness of electric current and magnetic field treatments for eliminating major viral pathogens in potato plant tissues. The experiments were conducted on cuttings and apical parts of potato plants infected with potato virus X (PVX), potato virus S (PVS), potato virus M (PVM), potato leafroll virus (PLRV), and potato virus A (PVA). Each treatment mode included four biological replicates (n=4). For PVX, PVS, PLRV and PVA, six modes were tested (24 samples per virus), while for PVM twelve modes were applied (48 samples). Samples were considered ELISA-negative when A405 (sample) < 3 x A405 (negative control). The plant material was exposed to electric currents ranging from 10 to 50mA for durations between 10 and 30min. Virus infection was diagnosed by enzyme-linked immunosorbent assay (ELISA) and reverse transcription PCR (RT-PCR); samples were considered virus-free when ELISA optical density values were lower than twice the mean absorbance of the negative control. The results demonstrated that the most effective electrotherapy parameters for PVM elimination were a current strength of 15–20mA and an exposure time of 20min. A comparable effect was observed for PVA using a current of 20mA for 30min. The antiviral effect of electrotherapy against PLRV persisted for one month in in vitro potato plants regenerated from cuttings treated with 20mA for 30min. The tested electrotherapy modes were ineffective in eliminating PVX and PVS. It was determined that prolonged exposure to electric current (>10min) can negatively affect the ability of plants to morphogenesis. Magnetic pulse treatment in the modes of 8, 16 and 32Hz did not ensure the elimination of PVX, PVY, PLRV and PVM. Magnetic treatment at a frequency of 8Hz of the Cerata and Colomba varieties led to a reduction in PVX and PVM content in potato tissues according to ELISA data.

Keywords: Potato viruses, Electrotherapy, Magnetic pulse treatment, In vitro culture, Virus elimination.

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INTRODUCTION

The use of virus-free seed tubers remains the most effective strategy for controlling viral diseases in potato crops. In recent years, there has been a global increase in the use of certified seed potatoes (Anisimov & Zebrin, 2018). Tissue culture techniques have been widely introduced into seed potato production systems in many countries. In this context, the development of effective virus-elimination technologies and the creation of an in vitro collection of a virus-free potato gene pool are important steps toward the certification and production of healthy planting material (Loebenstein et al., 2001). However, conventional methods for virus elimination in potatoes – such as meristem culture and thermotherapy – are often limited in efficiency, require extended treatment durations, and do not consistently result in complete viral eradication (Tokbergenova & Babayev, 2011). In this regard, there is growing interest in alternative and more effective approaches.

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Recent advances in plant biotechnology have provided deeper insight into the physiological mechanisms underlying the success and limitations of physical sanitation methods such as electrotherapy and magnetic pulse treatment. There is growing evidence that electrotherapy can have a positive effect on plants, stimulating their defense mechanisms and helping to suppress viral infections (Emami et al., 2011; AlMaarri et al., 2012; Bădărău et al., 2014). The mechanisms of electrotherapy's action on plant viruses are still not fully understood, but its potential as an effective method for protecting potatoes from viral diseases represents a promising area for further research and application in agriculture. Adil et al. (2022) in their study on electrotherapy mechanisms on plants claimed that electrotherapy can be used effectively to eliminate viruses from viral-infected plant material within a few minutes, thereby highlighting its optimal operation. They further explained that despite the positive effects in eliminating viruses, there exists the possibility of protein synthesis alteration due to the increased temperature. Adil et al. (2022) highlighted that there have been cases where treated plants displayed increased stem and regeneration without compromising their genetic integrity. Electrotherapy can influence plant tolerance to stressors like viruses and pathogens. Sukhova and Sukhov (2021), in their study on the effect of electric signals on plant tolerance, concluded that electrical signals can affect plant physiology, influencing respiration, photosynthesis, and the production of stress hormones. They further highlighted that by exposing plants to weak electric fields or specific electrical signals, there was a possibility to enhance plant resistance to stressors like toxic organic compounds by promoting beneficial bacteria in the root zone. Plants in general respond to electrical fields, which can affect their movement and growth. Adil et al. (2022) and Thanuja et al. (2025a) supported the claim that although electrotherapy alone is a more reliable method for producing virus-free plants, in some cases, it is important to consider the synergistic effect of combining the therapy with other virus-elimination techniques to achieve a higher virus-elimination efficiency rate. Studies have shown that by combining different therapies, the efficiency of treatments can be increased and limitations of the individual therapies can be overcome. By combining electrotherapy with, for example, thermotherapy, the thermal load on the plant is reduced, the treatable virus spectrum increases due to the physical and biochemical pressure, and there is a higher survival rate due to the reduced temperature. Combining with chemotherapy significantly REDUCES the limitation of phytotoxicity by enabling the use of lower, safer concentrations of the antiviral agent and likely REDUCES the limitation of potential mutagenicity for the same reason (lower chemical dose). It also modifies the limitation of genotype sensitivity, potentially making the treatment applicable to a wider range of genotypes, as the primary stressor becomes the electricity rather than a high chemical dose. Studies have also shown that two or more therapies can be combined to achieve optimal results (Magyar-Tábori et al., 2021; Mathew et al., 2020; Mirzaei et al., 2024a).

A new approach is magnetic pulse treatment (MPT), which, as a method of physical impact, has already proven itself in horticulture, in particular in the recovery of fruit trees and berry crops from viral infection. Thus, when using the stimulator SMI-5 *in vitro* culture to recover raspberries of the Malakhovka variety from the bushy dwarf virus, an increase in the yield of healthy plants by 67% was observed compared to the control. A similar effect was obtained for the Gerakl variety, where the number of recovered plants increased by 50% (Kulikov et al., 2015). Electrotherapy involves the passage of controlled electric current through plant tissues to inactivate viruses while maintaining cellular viability. The mechanism is considered multifactorial: electric current induces localized Joule heating, transient pore formation in plasma membranes, and modification of the electrochemical gradients that regulate ion homeostasis. These effects can lead to conformational changes in viral capsid proteins and disruption of viral RNA stability (Adil et al., 2022). Additionally, mild electrostimulation enhances endogenous defence signalling through reactive oxygen species (ROS) bursts and up-regulation of heat-shock proteins (HSP70, HSP90) that protect plant macromolecules under stress (Grzelka et al., 2023). However, the physiological window between virus inactivation and tissue damage is narrow. Excess current density or prolonged exposure can cause oxidative membrane injury, inhibition of photosystem II, and irreversible loss of meristem viability (Mirzaei et al., 2024b). Optimisation of current amplitude, treatment duration, and medium conductivity is therefore essential for successful electrotherapy protocols.

Beyond direct viral inactivation, electrotherapy also interacts with plant electrical signaling. Plants possess excitable membranes that respond to electric stimuli through calcium-dependent action potentials. Controlled stimulation has been shown to enhance phytohormone balance, particularly salicylic acid and jasmonic acid pathways, which are crucial for systemic acquired resistance. In *Nicotiana benthamiana*, sublethal electric treatments up-regulated WRKY transcription factors and PR1-gene expression, mirroring pathogen-triggered immunity responses (Zhang et al., 2023). These findings provide molecular evidence that electrotherapy functions not only as a destructive force to viruses but also as a trigger for innate plant immunity.

Pulsed magnetic field (PMF) exposure represents another promising physical sanitation tool with a distinct mechanism. Unlike continuous magnetic fields, PMFs deliver alternating electromagnetic pulses that penetrate plant tissues and influence ion transport, free-radical kinetics, and enzyme conformation. Experimental evidence shows that PMF treatments enhance antioxidant enzyme activities – superoxide dismutase, catalase, and peroxidase – leading to decreased lipid peroxidation and improved cellular redox balance (Tota et al., 2024). In metabolomic studies, PMF-treated pear and apple micro-plants displayed increased synthesis of phenolic compounds, flavonoids, and ascorbate, metabolites closely linked with

antiviral and antistress activity (Upadyshev et al., 2023). Magnetic exposure can also modulate gene expression of enzymes in the phenylpropanoid pathway and enhance lignin biosynthesis, potentially reinforcing cellular barriers against virus movement. Nevertheless, the biological responses to PMFs are highly dependent on field intensity, pulse frequency, exposure duration, and the species' intrinsic magneto sensitivity. Insufficient standardization of these parameters remains a major obstacle for reproducibility across laboratories.

Compared with physical methods, classical sanitation techniques – meristem culture, thermotherapy, chemotherapy, and cryotherapy – are well established but vary in efficiency and cost. Meristem culture exploits the low virus concentration in apical dome cells but depends on precise excision skills and viable shoot regrowth. Thermotherapy, generally at 35–40°C for 2–6 weeks, denatures viral proteins yet may cause heat stress and morphological abnormalities (Szabó et al., 2024). Chemotherapy using nucleoside analogues such as ribavirin interferes with viral replication but often reduces morphogenesis and induces mutagenic risk (Oves et al., 2024). Cryotherapy – rapid freezing of shoot tips in liquid nitrogen – achieves complete eradication for many viruses while retaining meristematic cells, though survival rates rarely exceed 50 % without post-thaw recovery treatments (Wang et al., 2022). Increasingly, researchers advocate hybrid strategies: thermotherapy or electrotherapy to lower viral titre, followed by meristem excision or cryotherapy to secure complete sanitation (Thanuja et al., 2025b). These converging studies highlight that integrating electrotherapy and PMF treatments into conventional in vitro sanitation systems could shorten treatment duration, enhance viral elimination rates, and improve plant recovery by priming stress-tolerance pathways. However, systematic evaluation of genotype-specific thresholds, cumulative stress effects, and molecular markers of virus clearance remains essential before these methods can be standardized for large-scale seed potato certification programs.

The effectiveness of this approach has also been confirmed for potatoes. A method for treating potato plants against viral infections using a high-intensity (3–5 T) and high-frequency (4–51kHz) pulsed magnetic field has been described. Microcuttings 10–12mm long were treated with a pulse number of 1 to 5 and an interval of 2–3 seconds between them. According to the results of ELISA diagnostics, up to 100% of healthy plants were obtained 30 days after cultivation, indicating the high effectiveness of the selected mode (Shevchenko et al., 2021). Collectively, these findings suggest that pulsed magnetic field exposure can be successfully applied to both woody and herbaceous crops, including potatoes. This allows us to consider magnetic treatment as a promising physical method aimed at improving the health of the source material and reducing the viral load in *in vitro* biotechnological systems.

Magnetic pulse (MP) treatment, which involves magnetic fields, can enhance plant defense metabolism by stimulating the production of defensive compounds, such as antioxidants and proteins, and by altering the plant's physiological response to stress. Saletnik et al. (2022) highlighted that the action of magnetic fields increases the activity of antioxidant enzymes, reducing oxidative stress. Static magnetic fields also have a strong influence on the cell's shape and membrane structure, increasing permeability and affecting metabolic pathway activity. Magnetic treatments, such as MPT and PMT, on plants can also increase the content of proteins, carbohydrates, soluble and reducing sugars, and, in some cases, lipids and fatty acid composition, as well as influence macro- and microelement uptake and gene expression at various levels. These cumulative effects, which include oxidative damage reduction, stress tolerance improvement by accumulating defense metabolites like proline and proteins, and influencing cell-level processes like membrane permeability and calcium signaling, are critical for activating local defenses (Sarraf et al., 2020; Abdulraheem et al., 2025).

The aim of this study is to evaluate the effectiveness of electrotherapy and magnetic pulse treatment for the elimination of major viruses from *in vitro* potato tissues. The present study is designed to comprehensively evaluate the efficacy of electrotherapy and magnetic pulse treatment in eliminating the principal viral pathogens of potato (PVX, PVY, PVS, PVM, PLRV, and PVA) under in vitro conditions. It is hypothesized that the effectiveness of virus eradication would depend on the interaction between the applied electric current or magnetic field parameters (intensity and exposure duration) and the biological characteristics of the infecting virus. Furthermore, it is also assumed that moderate current strengths (15–20mA) and low-frequency magnetic pulses (approximately 8Hz) will promote selective viral inactivation while preserving the morphogenic capacity of potato explants. By systematically varying these treatment parameters, the study seeks to identify optimal regimes that ensure maximal viral elimination with minimal adverse effects on plant regeneration, thereby contributing to the advancement of biotechnological methods for producing virus-free potato material.

Accordingly, this study pursued three specific objectives: (i) to quantify the efficiency of electrotherapy under varying current intensities (15–50mA) and exposure durations (10–30min) for the elimination of *Potato virus X*, *Potato virus S*, *Potato virus M*, *Potato leafroll virus*, and *Potato virus A*; (ii) to assess the influence of electrotherapy on plant morphogenesis and regeneration capacity under *in vitro* conditions; and (iii) to determine whether magnetic-pulse treatment at different frequencies (8, 16, and 32Hz) modulates viral load or plant physiological responses. We hypothesized that (a) current × duration interactions would differentially affect virus elimination efficiency among virus species; (b) higher current intensities and longer exposure times would increase viral suppression but concomitantly reduce morphogenic potential; and (c) magnetic-pulse treatment at low frequencies (≈ 8 Hz) would not fully eradicate infection but could reduce viral RNA concentration and stimulate antioxidant defense metabolism.

MATERIALS & METHODS

The objects of the study were natural isolates of PVX, PVY, PVS, PVM, PLRV and PVA, with which potato tubers were infected during cultivation in the field. Potato tubers infected with PVX, PVY, PVS, PLRV and PVA were kindly provided by the Institute of tuber crop research, College of Agronomy and Biotechnology, Southwest University (Chongqing, China). Potato tubers infected with PVM were obtained from the Tatar Research Institute of Agriculture, Kazan Scientific Center (Kazan, Russia). Sprouts of infected tubers were sterilized (Rubtsov et al., 2017) and transferred for cultivation under aseptic conditions to an artificial nutrient medium. Virus-infected *in vitro* potato plants were cultured in test tubes on Murashige and Skoog (MS) agar medium at a temperature of +20-+25°C, relative humidity of 50–70%, and a photoperiod of 16h light/8h dark (Lavrynenko et al., 2016). *In vitro* propagation of plants was carried out by cuttings. Testing of the initial infected potato tuber sprouts for virus infestation before introduction into *in vitro* culture, and micro plants, after introduction into *in vitro* culture, was carried out using the enzyme-linked immunosorbent assay (ELISA) method. For this purpose, the LOEWE complete kit (Germany) was used for the diagnosis of PVX (#07037), PVS (#07034), PVM (#07033), PLRV (#07031), PVA (#07035), PVY (#07032) according to the manufacturer's instructions (LOEWE, 2021). Optical density was read on a StatFax 4200 device (USA) at a wavelength of 405nm.

Samples were considered ELISA-negative when A405 (sample) <3 x A405 (negative control). RNA quality and integrity were assessed prior to RT-PCR by measuring the A260/280 ratio (acceptable range 1.8–2.1) and by confirming intact rRNA bands on a 1.5% agarose gel. Primer sequences for all viruses were taken from the official diagnostic standard NY/T 2678-2015 (Ministry of Agriculture of China), which provides validated oligonucleotide sets and reaction parameters for PVX, PVY, PVS, PVM, PLRV, and PVA. To investigate the effect of electric current on virus elimination (electrotherapy), *in vitro* micro-cuttings (20mm) were placed in a Mini-Plus Horizontal HU10 electrophoresis chamber (Scie-Plas, UK) with the apical end oriented toward the cathode. The chamber was filled with 1M NaCl solution, and electric current was applied using an EV245 power supply (Consort, Belgium). Cuttings were treated with electric current ranging from 15 to 50mA for exposure durations of 10, 20, or 30min (Table 1).

The distance between the electrodes in the HU10 chamber was 70mm, and the working solution volume was approximately 120mL. The conductivity of the 1M NaCl solution was monitored before each run and remained within 82–85mS/cm at 22°C. Treatments were performed in constant-current mode; depending on the applied current (15–50mA), the EV245 power supply generated voltages ranging from 9 to 22V. This corresponded to an electric field strength of approximately 1.3–3.1V/cm across the explants. Temperature inside the chamber was monitored with a micro-thermocouple placed adjacent to the cuttings; during all treatments the temperature increase did not exceed 1.5–2.0°C, allowing a clear separation between thermal and non-thermal effects.

In the experiment to study the effect of electrotherapy on PVA, PVX, PLRV, PVS, PVM isolates, four cuttings of micro plants were used for each experimental variant. Three were analyzed by RT-PCR immediately after treatment, and one was transferred to MS agar medium for further growth and subsequent RT-PCR analysis. Magnetic pulse treatment of virus-infected cuttings of *in vitro* plants was carried out using a device of original design (Donetskikh et al., 2018). The length of the treated cuttings was 10mm. The device generated pulsed magnetic fields with an intensity of 90–120mT at the center of the coil, with a pulse width of 2–3ms and a duty cycle of approximately 20%. The solenoid contained 250 turns of copper wire, and cuttings were positioned vertically in the central axis of the coil so that the long axis of the explant was parallel to the magnetic field lines. Ambient temperature during MPT did not exceed 24–25°C, and coil surface temperature was monitored to ensure that no thermal elevation (>1°C) occurred during exposure.

Table 1: Scheme of the experiment on *in vitro* treatment of potato cuttings infected with viruses with electric current and magnetic field

Option	Exposition	Current strength / Frequency of electromagnetic waves
Electrotherapy of cuttings infected with PVX, PVS, PVM, PLRV, PVA		
Option E-0	Control (no treatment)	
Option E-1	10min	15 mA
Option E-2	20min	15 mA
Option E-3	30min	15 mA
Option E-4	10min	20 mA
Option E-5	20min	20 mA
Option E-6	30min	20 mA
Electrotherapy of PVM infected cuttings (additional modes)		
Option E-7	20min	30 mA
Option E-8	30min	30 mA
Option E-9	20min	40 mA
Option E-10	30min	40 mA
Option E-11	20min	50 mA
Option E-12	30min	50 mA
Magnetic treatment cuttings infected with PVX, PVM, PVY, PLRV		
Option M-0	Control (no treatment)	
Option M-1	15min	8 Hz
Option M-2	15min	16 Hz
Option M-3	15min	32 Hz

Detection of viral RNA in both initial and treated samples was performed using RT-PCR. Isolation of nucleic acids was carried out using "RIBO-sorb" kit (#K2-1-Et-100, AmpliSens, Russia), according to the instructions for the kit. RNA concentration was determined using the VWR mySPEC Twin Touch spectrophotometer (Copenhagen Nanosystems A/S, Denmark). Reverse transcription was performed using the "REVERTA-L" kit (#K3-4-100, AmpliSens, Russia) according to the kit instructions. The reaction mixture for PCR was prepared using Taq 2X Master Mix (#M0270, New England Biolabs, USA). To detect potato viruses by PCR, pairs of specific oligonucleotides were added to the reaction mixture (NY/T 2678-2015, 2015): PVS-F (5'-gaggctatgctggagcagag) and PVS-R (5'-aatctcagcgccaagcatcc), fragment length 729 bp; PVX-F (5'-atgtcagcaccagctagca) and PVX-R (5'-tggtggtggtagagtgacaa), fragment length 711 bp; PVY-F (5'-ggcatacggacataggagaaact) and PVY-R (5'-ctctttgtgttctcctcttgtgt), fragment length is 447 bp; PVM-F (5'-acatctgaggacatgatgcgc) and PVM-R (5'-tgagctcgggaccattcatac), fragment length is 520bp; PLRV-F (5'-cgcgctaacagagttcagcc) and PLRV-R (5'-gcaatgggggtccaactcat), fragment length is 336bp; PVA-F (5'-gatgtcgatttaggtactgctg) and PVA-R (5'-tccattctcaatgcaccatac), fragment length is 273bp. PCR was performed on a C1000 Touch™ Thermal Cycler (Bio-Rad, USA) under the following temperature conditions: 1 cycle: 96°C – 3min; 29 cycles: 96°C – 20 seconds, 55°C – 20 seconds, 72°C – 1 minute; 1 cycle: 72°C – 5min. PCR results were visualized on 1.5% agarose gel containing TAE buffer and 0.01% ethidium bromide. Results were detected using the Gel Doc XR+ video documentation system (BioRad, USA). The size of the amplified fragments was determined relative to the molecular size marker Quick-Load 100bp DNA Ladder (New England Biolabs, USA).

Statistical analysis of the results was carried out in Microsoft Excel 2016. Virus elimination outcomes (virus detected / not detected by RT-PCR) were analysed using two-sided Fisher's exact tests, with each explant (cutting or apical segment) treated as a biological replicate (n=1). For each treatment mode, a 2×2 contingency table (treated vs control × eliminated vs not eliminated) was constructed, and exact p-values were calculated. The significance level was set at α=0.05, and Holm correction was applied within each virus group to control the family-wise error rate. Effect sizes were reported as risk difference with 95% confidence intervals. Differences in plant height after electrotherapy were evaluated by one-way ANOVA followed by LSD (0.05) for multiple comparisons. Assumptions of normality and homogeneity of variance were assessed using residual plots.

RESULTS

The initial infection status of potato samples was verified using ELISA and RT-PCR methods. After transferring the plants to aseptic culture conditions, the presence of viruses was confirmed in all the studied initial samples (Table 2, Fig. 1). It was found that after the treatment of PVM-infected cuttings with an electric current of 15-50mA, the virus elimination was observed in the cuttings exposed to a current of 15-40mA for all three studied exposure times (10, 20, 30min) (Table 3). Out of the 12 tested electric current treatment modes for potato plants, 5 experimental variants proved to be effective, showing cases of PVM elimination. In these variants, a total of 7 plants free from PVM infection were reliably obtained. The negative RT-PCR result in one potato sample treated with an electric current of 15mA for 10min was not recognized by us as reliable due to the low concentration of RNA in the nucleic acid preparation, and the healing effect of electrotherapy in this case was not taken into account. During the electrotherapy process, PVM elimination was observed only in the cuttings, but not in the apical parts of the in vitro plants.

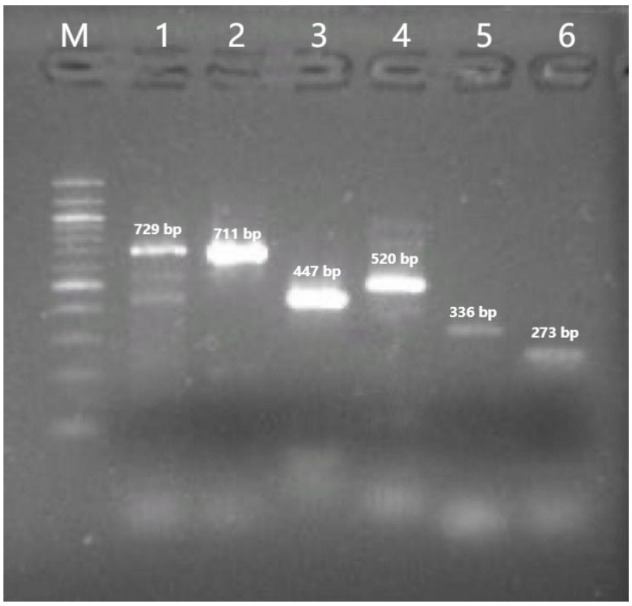

Fig. 1: Results of virus diagnostics in infected *in vitro* potato plants by RT-PCR method; M - Quick-Load 100 bp DNA Ladder; 1 - potato infected with PVS; 2-potato infected with PVX; 3-potato infected with PVY; 4-potato infected with PVM; 5 - potato infected with PLRV; 6 - potato infected with PVA.

The most effective in terms of PVM removal were the two electrotherapy modes: 15mA for 20min and 20mA for 20min. In these experimental variants, PVM elimination was detected in 2 of the 4 studied cuttings subjected to electrotherapy. Calculation of the nonparametric Fisher's exact test revealed that the differences detected between these variants and the control were statistically significant (p=0.035). Across all PVM treatment modes, the aggregated elimination rate was 7/48 (14.6%; 95% CI: 7.2–27.2%). For the most effective modes (15mA × 20min and 20mA × 20min), the elimination frequency (2/4) differed significantly from the control (0/12), with a risk difference of 0.50 (95% CI: 0.12–0.88).

Exposure of potato cuttings to electric currents of 15 and 20mA for 10, 20 and 30min did not result in the elimination of PVX, PVS and PLRV (Table 4). For PVX and PVS, elimination was not observed in any treatment mode (0/24 for each virus). Fisher's exact tests showed no statistical difference from the respective controls (p=1.000), with 95% confidence intervals for possible elimination success ranging from 0 to 13.8% under the tested conditions.

Table 2: Results of detection of viruses infected *in vitro* potato plants by ELISA, optical units

Sample name	PVX	+/-	PVS	+/-	PVM	+/-	PLRV	+/-	PVA	+/-	PVY	+/-
Initial sample	0.499	+	0.304	+	0.585	+	0.211	+	0.326	+	0.467	+
Positive control	0.747	+	3.036	+	1.362	+	0.530	+	0.341	+	0.585	+
Negative control	0.080	-	0.069	-	0.073	-	0.065	-	0.087	-	0.075	-

Note: "+" – presence of virus, "-" – absence of virus.

Table 3: Effect of electrotherapy on the elimination of PVM from potato cuttings

Electric current treatment mode	Part of a plant	RNA concentration, ng/μL	Elimination, +/-
Control	Cutting	20.631	-
(without treatment)	Cutting	25.462	-
	Cutting	65.747	-
	Cutting	27.779	-
	Cutting	23.581	-
	Cutting	29.074	-
	Cutting	24.499	-
	Cutting	20.631	-
	Cutting	63.233	-
	Apical segment	16.427	-
	Cutting	31.089	-
	Cutting	22.004	-
	Cutting	43.470	-
	Apical segment	17.473	-
	Cutting	32.596	-
10min 15 mA	Cutting	2.979	-
	Cutting	7.016	-
	Apical segment	10.077	-
	Cutting♦	9.268	-
10min 20 mA	Cutting	9.154	-
	Apical segment	12.750	-
	Apical segment	13.814	-
	Cutting♦	18.383	-
20min 15 mA	Cutting	40.553	+
	Cutting	12.641	+
	Cutting	13.255	-
	Cutting♦	26.258	-
20min 20 mA	Cutting	12.010	+
	Cutting	14.656	+
	Cutting	17.966	-
	Cutting♦	14.389	-
20min 30 mA	Cutting	12.011	-
	Cutting	21.980	-
	Cutting	10.103	-
20min 40 mA	Cutting	21.497	-
	Cutting	16.259	-
	Cutting	12.329	-
	Cutting	15.604	-
20min 50 mA	Cutting♦	13.112	-
	Cutting	17.242	-
	Cutting	17.345	-
	Cutting	12.828	-
30min 15 mA	Apical segment	23.799	-
	Apical segment	18.515	-
	Cutting	22.448	-
	Cutting♦	18.392	-
30min 20 mA	Cutting	31.235	-
	Cutting	22.608	-
	Cutting	14.473	+
	Cutting♦	27.379	-
30min 30 mA	Cutting	10.706	+
	Cutting	11.879	-
	Cutting	10.568	-
30min 40 mA	Cutting	12.912	-
	Cutting	10.846	+
	Cutting	16.638	-
	Cutting	12.780	-
30min 50 mA	Cutting	10.714	-
	Cutting	11.350	-
	Cutting	15.316	-
	Cutting	34.053	-

Note: ♦ - virus detection was carried out after *in vitro* plant cultivation.

PVA elimination during electrotherapy of potato cuttings with current of 15 and 20mA for 10, 20 and 30min was detected using four modes of electric current treatment out of eight applied modes. Moreover, PVA elimination was reliably recorded in 5 potato samples out of 18 studied samples. PVA elimination from *in vitro* plant tops with electric current treatment was significantly worse than in cuttings, but in one case (20min 20 mA mode) PVA elimination in the plant top was successful. The most effective in terms of PVA removal was treatment with an electric current of 20mA for 30min. In this case, PVA elimination was detected in 2 of 3 experimental cuttings. The detected differences with the control variant are statistically significant ($p=0.045$; Fisher's exact test). Across all PVA treatment modes, 5/18 cuttings were virus-free (27.8%; 95% CI: 12.5–50.9%). The mode 20mA × 30min showed the highest elimination rate (2/3), which was significantly higher than the untreated control.

In vitro plants grown from cuttings subjected to various electrotherapy regimens were in the vast majority of cases infected with viral pathogens. However, in one case (treatment with 20 mA current for 30min), a healing effect of PLRV electrotherapy was detected, which persisted for 30 days of the entire subsequent cycle of growing the *in vitro*-formed plant. This elimination event corresponded to 1/4 PLRV-tested cuttings (25%; 95% CI: 4.6–69.9%). Because the effect manifested only after regeneration, Fisher's exact comparison with the immediate post-treatment controls did not reach statistical significance ($p=0.293$).

The results of the study of the morphogenic capacity of potato cuttings treated with electric currents from various viruses are presented in Table 5.

In some cases, treating plants with current for more than 10min leads to a decrease in their ability to morphogenesis. Quantitative assessment of morphogenesis (Table 5) showed a clear interaction between current intensity and exposure duration. Across all viruses, treatments exceeding 10min frequently reduced plant height to <3.0cm and resulted in a "–" morphogenesis score, especially under 20–30mA × 20–30min. PVS- and PVA-infected cuttings generally maintained higher morphogenic capacity under 10–20mA for 10–20min, whereas PVM- and PLRV-infected cuttings were more susceptible to growth suppression at longer exposures. These observations indicate that both the viral background and the duration of electric stress significantly influence regenerative performance. The relative standard error for the entire sample was 6.5%, indicating an acceptable level of data dispersion within biological experiments.

During the research, an experiment was conducted on magnetic-pulse treatment of *in vitro* cuttings of plants infected with viruses. The results of diagnostics of viral pathogens in plants after magnetic treatment are presented in Table 6. As a result of the impact of the applied magnetic treatment modes on the cuttings of potato plants infected *in vitro*, no virus elimination was observed.

Table 4: Effect of electric current on the process of virus elimination from potato cuttings

Electric current treatment mode	Part of a plant	RNA concentration. ng/μL	Elimination. +/-
PVA			
Control	Cutting	25.924	-
(without treatment)	Cutting	24.417	-
	Cutting	31.529	-
	Cutting	18.326	-
	Cutting	30.271	-
	Cutting	28.422	-
	Cutting	41.421	-
	Cutting	21.648	-
	Cutting	17.421	-
10min 15 mA	Apical segment	26.974	-
	Cutting	25.270	-
	Cutting	28.132	-
	Cutting♦	24.382	-
10min 20 mA	Apical segment	43.900	-
	Apical segment	23.778	-
	Cutting	22.087	+
	Cutting♦	29.379	-
20min 15 mA	Apical segment	41.047	-
	Apical segment	34.874	-
	Cutting	26.845	+
	Cutting♦	32.682	-
20min 20 mA	Apical segment	19.491	-
	Apical segment	23.265	+
	Cutting	30.494	-
	Cutting♦	26.179	-
30min 15 mA	Cutting	34.232	-
	Apical segment	37.227	-
	Cutting	30.590	-
30min 20 mA	Cutting	21.900	-
	Cutting	21.130	+
	Cutting	24.371	+
PVX			
Control	Cutting	56.461	-
(without treatment)	Cutting	9.837	-
	Cutting	35.940	-
	Cutting	15.988	-
	Cutting	15.576	-
	Cutting	16.839	-
	Cutting	63.136	-
	Cutting	22.677	-
	Cutting	20.690	-
	Cutting	32.655	-
10min 15 mA	Cutting	22.934	-
	Apical segment	19.597	-
	Cutting	41.670	-
	Cutting♦	31.257	-
10min 20 mA	Cutting	21.880	-
	Cutting	25.870	-
	Cutting	20.230	-
20min 15 mA	Cutting	24.833	-
	Cutting	38.032	-
	Cutting	23.410	-
	Cutting♦	35.390	-
20min 20 mA	Cutting	19.790	-
	Cutting	18.840	-
	Cutting	33.252	-
30min 15 mA	Cutting	33.080	-
	Cutting	17.159	-
	Apical segment	43.437	-
	Cutting♦	26.381	-
30min 20 mA	Apical segment	29.876	-
	Cutting	39.372	-
	Cutting	18.337	-
PLRV			
Control	Cutting	14.483	-
(without treatment)	Cutting	17.216	-
	Cutting	14.348	-
	Cutting	35.892	-
	Cutting	26.382	-
	Cutting	18.541	-
	Cutting	27.718	-
	Cutting	18.512	-
	Cutting	29.412	-
10min 15 mA	Cutting	17.786	-
	Cutting	25.124	-
	Apical segment	46.248	-
	Cutting♦	29.365	-
10min 20 mA	Cutting	14.688	-
	Cutting	22.095	-
	Apical segment	10.329	-
	Cutting♦	21.493	-
20min 15 mA	Cutting	29.435	-
	Cutting	21.011	-
	Cutting	15.880	-
	Cutting♦	16.382	-
20min 20 mA	Cutting	28.001	-
	Apical segment	26.619	-
	Cutting	13.201	-
30min 15 mA	Cutting	5.187	-
	Apical segment	22.997	-
	Cutting	98.078	-
30min 20 mA	Cutting	33.638	-
	Cutting	12.471	-
	Cutting	24.477	-
	Cutting♦	27.219	+
PVS			
Control	Cutting	26.389	-
(without treatment)	Cutting	18.368	-
	Cutting	35.279	-
	Cutting	52.467	-
	Cutting	16.368	-
	Cutting	28.362	-
	Cutting	27.171	-
	Cutting	19.621	-
	Cutting	39.618	-
10min 15 mA	Cutting	21.567	-
	Cutting	20.368	-
	Cutting	32.864	-
	Cutting♦	30.279	-
10min 20 mA	Cutting	35.595	-
	Cutting	25.052	-
	Cutting	17.847	-
	Cutting♦	23.489	-
20min 15 mA	Apical segment	17.036	-
	Apical segment	29.378	-
	Apical segment	16.382	-
	Cutting♦	23.478	-
20min 20 mA	Cutting	25.739	-
	Cutting	16.037	-
	Cutting	17.394	-
	Cutting♦	14.384	-
30min 15 mA	Cutting	10.382	-
	Apical segment	26.784	-
	Cutting	49.389	-
	Cutting♦	32.482	-
30min 20 mA	Cutting	24.048	-
	Cutting	24.238	-
	Cutting	17.382	-

Note: ♦ - virus detection was carried out after *in vitro* plant cultivation.

At the same time, a decrease in the RNA concentration was noted in cuttings infected with PVM and PVY NTN when treated with a magnetic field with a frequency of 8Hz. Analysis of the effect of magnetic treatment with a frequency of 8Hz on viruses in three potato varieties showed that the effect depended on the type of virus, the concentration of the virus and varietal characteristics (Table 7). In the innovator variety, magnetic treatment did not contribute to the elimination of PVX. In contrast, in the Cerata variety, the PVX infection index according to ELISA decreased by 2.4 times compared to the control (without treatment) and was at the level of the seronegative control. At the same time, a decrease in RNA concentration by

22.6% was noted compared to the control variant. According to ELISA data, in the cuttings of the Colomba variety, the PVM infection index after magnetic pulse treatment decreased by 1.8 times compared to the variant without treatment. Consequently, magnetic treatment with a frequency of 8Hz on the varieties Cerata and Colomba resulted in a decrease in the content of PVX and PVM in potato tissues.

Table 5: Morphogenic capacity and average height of potato plants one month after electrotherapy

Virus	Processing option	Plant height after a month of cultivation on MS.cm	Morphogenic ability. +/-
PVX	10min 15 mA	3.0±0.9	+
	20min 15 mA	2.0±0.7	-
	30min 20 mA	11.0±1.1	++
PVS	10min 15 mA	7.0±1.0	++
	10min 20 mA	7.0±1.1	++
	20min 15 mA	5.0±0.8	++
	20min 20 mA	6.0±1.3	++
	30min 15 mA	2.0±0.6	-
	30min 30 mA	2.0±0.6	-
PVM	10min 15 mA	3.0±0.8	+
	10min 20 mA	10.0±1.4	++
	20min 15 mA	2.0±0.7	-
	20min 20 mA	3.0±0.9	+
	30min 20 mA	2.0±0.6	-
PLRV	10min 15 mA	7.0±1.0	++
	10min 20 mA	7.0±1.2	++
	20min 15 mA	7.0±1.1	++
	30min 20 mA	2.0±0.7	-
PVA	10min 15 mA	7.0±1.1	++
	10min 20 mA	10.0±1.3	++
	20min 15 mA	6.0±1.0	++
	20min 20 mA	7.0±1.1	++
LSD(0.05)		0.9	
m. %		6.5%	

Note: ++ – intensive growth. active formation of new shoots and organs; + – weak morphogenesis; - – absence of morphogenesis. growth cessation; 6.5% (relative standard error for the entire dataset).

DISCUSSION

In this study, the effectiveness of electrotherapy and magnetic pulse treatment for the recovery of potato microplants infected with viral pathogens was evaluated. The results obtained demonstrate the high efficiency of electrotherapy in the elimination of potato viral infections, in particular PVM, PVA and PLRV. Electrotherapy showed a selective effect depending on the type of virus and the exposure mode, which emphasizes the importance of selecting the current parameters, taking into account the biological characteristics of the pathogen and the culture. The structural characteristics of PVA may influence its sensitivity to electrotherapy. Virions of this virus have a curved thread-like shape, reaching a length of 680-750nm and a width of 11-13nm. They contain a single-stranded polyadenylated positive-sense RNA genome (Wu et al., 2021). The main route of PVA transmission in the field is non-persistent spread with the participation of aphids (Fox et al., 2017). In potato crops, PVA-infected plants often show mild mosaic symptoms on the leaves. According to the results of Yanlin Li's research, PVA was effectively eliminated from infected plants at a temperature of 36°C, especially when combined with thermotherapy and *in vitro* apical meristem culture (Li et al., 2016). Potato plants infected with PVA were cured by using low doses of ribavirin during chemotherapy, while higher concentrations of the drug were required to eliminate PLRV and PVM viruses (Oves et al., 2024). In addition, the use of cryotherapy allowed successful curing of PVA-infected potato varieties, while complete elimination of PVX virus

Table 6: Results of magnetic treatment of potato cuttings in relation to virus isolates based on detection by the PCR method

Magnetic field treatment mode	Clone	RNA concentration. ng/μL	Elimination. +/-
PVX			
Control	PVX1	56.461	-
(without treatment)	PVX2	9.837	-
	PVX3	35.940	-
	PVX4	15.988	-
	PVX5	15.576	-
8 Hz	PVX1	7.037	-
	PVX1	6.013	-
	PVX2	12.943	-
	PVX3	21.011	-
	PVX4	27.274	-
	PVX5	10.556	-
16 Hz	PVX1	16.839	-
	PVX1	63.136	-
	PVX2	22.677	-
	PVX2	20.690	-
	PVX3	32.655	-
	PVX3	12.945	-
	PVX4	17.543	-
	PVX5	18.336	-
32 Hz	PVX1	12.026	-
	PVX1	19.071	-
	PVX2	20.574	-
	PVX2	43.568	-
	PVX3	32.259	-
	PVX4	19.878	-
	PVX5	6.182	-
PVM			
Control	PVM1	25.462	-
(without treatment)	PVM2	65.747	-
	PVM3	27.779	-
	PVM4	23.581	-
	PVM5	29.074	-
8 Hz	PVM1	6.398	-
	PVM2	43.754	-
	PVM3	6.643	-
	PVM4	13.023	-
	PVM5	8.194	-
	PVM5	15.795	-
16 Hz	PVM1	26.950	-
	PVM1	23.201	-
	PVM2	22.226	-
	PVM3	15.924	-
	PVM4	154.739	-
	PVM5	54.310	-
32 Hz	PVM1	7.919	-
	PVM1	50.689	-
	PVM2	5.407	-
	PVM3	18.798	-
	PVM4	2.383	-
	PVM5	19.307	-
PVY			
Control	PVY NTN1	43.992	-
(without treatment)	PVY O1	26.270	-
	PVY O1	34.106	-
8 Hz	PVY NTN1	3.808	-
	PVY NTN1	14.000	-
16 Hz	PVY NTN2	25.011	-
	PVY NTN1	46.540	-
32 Hz	PVY NTN2	84.569	-
	PVY O1	31.387	-
PLRV			
Control (without treatment)	PLRV1	14.483	-
16 Hz	PLRV1	17.216	-
32 Hz	PLRV1	7.651	-

Table 7: Effect of magnetic treatment on viruses in in vitro potato plant cuttings

Option	Innovator (PVX)			Cerata (PVX)			Colomba (PVM)		
	Extinction	Infection index*	RNA concentration. ng/μL	Extinction	Infection index*	RNA concentration. ng/μL	Extinction	Infection index*	RNA concentration. ng/μL
Control (no treatment)	0.341	2.7	5.721	0.327	2.6	23.963	0.245	2.2	11.870
Magnetic pulse treatment 8 Hz	0.412	3.3	12.898	0.138	1.1	19.544	0.138	1.2	13.453

Note: * Infection index is the ratio of sample extinction to the extinction of the negative control.

from plants was difficult (Bespalova et al., 2020). Our study showed that the optimal electrotherapy regimes for PVA elimination were 15-20mA for 10-30min, which is a faster and less stressful method compared to the study by Emami Meybodi, in which the highest efficiency was achieved with the current of 35mA for 20min, which significantly reduced the concentration of PVA and PVY viruses. This may be due to the fact that, as indicated in this study, the effectiveness of electrotherapy depends on the varietal characteristics of potatoes (Emami et al., 2011). In our case, electrotherapy in the tested modes did not demonstrate effectiveness against the PVX isolate, while the study (Bădărău et al., 2014) confirmed the possibility of eliminating this virus with a current of 100 mA for 10min. This discrepancy may be due to the fact that in the experiment of these researchers, the treatment was carried out on plants in vivo, and then they were transferred to in vitro culture.

During the study, the elimination effect was predominantly observed in single-node cuttings rather than apical cuttings, which may be due to the fact that apical cuttings have more leaves and, accordingly, require longer processing than cuttings with an upper cut, as well as with two-sided access of the vascular system of the cutting for electrical currents and the movement of viral RNA, since the main plant viruses spread along the phloem after primary infection (Maule & Palukaitis, 1991; Dupuis, 2017). Exposure to electric current for more than 10min was in some cases accompanied by a decrease in the morphogenic capacity of plants. The decrease in regenerative capacity may be associated with damage to the tissues of potato cuttings as a result of prolonged stress exposure to the electric field. It is assumed that the main mechanism of action of electrotherapy is associated with the release of heat in tissues during the passage of electric current, which causes denaturation of viral proteins and makes the virus inactive, but can also overheat plant tissues (Gonzalez et al., 2006). This indicates the need to select an optimal electrotherapy regimen that ensures effective elimination of the virus while maintaining the ability of explants to form shoots.

The use of electrotherapy against PVY is more common in the literature (Mahmoud et al., 2009; Petrov & Lyubenova, 2011; AlMaarri et al., 2012). However, these studies examined potato viruses, which have previously been studied to a lesser extent by electrotherapy. Magnetic pulse treatment in the studied modes did not ensure the elimination of viruses on the isolates of PVX, PVY, PLRV and PVM viruses, however, at a frequency of 8Hz, a decrease in the concentration of viruses was noted in relation to the isolates of PVM and PVY NTN. Magnetic treatment with a frequency of 8Hz on the varieties of Cerata and Colomba led to recovery from PVX and PVM viruses. It can be assumed that the effect of magnetic treatment depends on the concentration of the virus and its interaction with the host plant. In the case of a high concentration of the virus, the best effect can probably be provided by a set of health measures, including, along with magnetic treatment, for example, thermo- and/or chemotherapy, which was demonstrated on horticultural crops (Upadyshev et al., 2025). The effect of magnetic treatment depends on the degree of development of non-specific resistance and activation of the synthesis of phenolic compounds, including salicylic acid (Upadyshev et al., 2021, 2023).

Differentiating between the biophysical modes of electrotherapy is crucial. While electric-current treatments have the potential to generate localized heating, their antiviral effects seem to primarily stem from the direct inactivation of virions, rather than merely isolating uncontaminated meristematic tissue (Magyar-Tábori et al., 2021). The basis of virus eradication under electrotherapy is not solely due to the high temperature, according to Magyar-Tábori et al. (2021), suggesting a primarily non-thermal (electroporation-like) mechanism. Classical thermotherapy, on the other hand, only uses heat stress, which can denature viral proteins and RNA while also causing phytotoxic stress to the plant.

Notably, electrical pulses administered at precise doses can destroy viruses without compromising the host's capacity to develop. The structural biology of the virus is also probably important: tightly packed genomes like DNA and RNA may withstand heat differently than single-stranded RNA, and filamentous (helical) viruses may orient and react to electric fields differently than quasi-spherical (icosahedral) viruses. The fact that phloem-limited viruses are generally easier to eradicate than viruses that invade meristematic cells implies that virion location and mobility are crucial, despite the paucity of empirical data on shape-specific sensitivity in plants. An apical cutting will, in fact, experience less current and contain fewer virions than a basal segment rich in phloem because current flow in an explant will follow the vascular conduits. These factors align with recent research demonstrating the absence of a one-size-fits-all sanitation methodology. Karan (2021) highlighted that PVS, PVA, and PVM could not be eradicated by thermotherapy or cryotherapy alone; the virus-removal rates varied greatly (50–100%) depending on the host and virus, according to Thanuja et al. (2025a), who reviewed several in vitro techniques (chemo-, thermo-, cryo-, and electrotherapy and meristem culture, and their combinations).

According to Magyar-Tábori et al., electrotherapy can pair with other therapies, like chemotherapy, to boost effectiveness. Therefore, stacked therapies should be used to treat strains that are high-titer or meristem-invading and do not respond to single cures. To further weaken viral particles in cases of extremely high viral load, one may

even parallelize electrotherapy with chemotherapies or thermotherapies or consider new tools like magnetic pulse treatment (MPT). Previous studies have shown that the effectiveness of short magnetic pulses for virus sanitation varies by species and magnetic field type, indicating that in some cases, electrotherapy and optimized MPT protocols could be used together. Even though MPT is still in the experimental stage, it might complement electrotherapy if the pulse parameters are carefully calibrated. We must also recognize the current work's limitations. Statistical robustness is limited because sample sizes for each treatment were small. Protocols must be standardized before widespread use because results are probably sensitive to the particular tools and configurations used (electrode geometry, medium conductivity, field strength, pulse duration, etc.). Furthermore, the 30-day follow-up period was insufficient to ensure sustained virus eradication. Future research should employ an extended validation strategy to overcome these constraints. In particular, regenerants should be indexed under greenhouse or field conditions for symptom recovery, and the viral load should be quantitatively monitored (e.g., by qPCR or RT-qPCR) at several timepoints for at least 90 days. Combining molecular assays with biological indexing would validate the cure (Singh et al., 2021).

Lastly, electrotherapy and MPT should be optimized and generalized in future studies. Modeling the current distribution in plant tissues to determine probable hot spots of virus inactivation and designing electrodes or chambers to deliver uniform fields through various explant types are two examples of this. How to maximize viral damage while preserving host viability would be made clear by thorough biophysical investigations of electroporation thresholds in plant cells versus virions (possibly on isolated membranes or empty capsids). MPT regimens could be defined by systematically screening the frequencies, intensities, and durations of magnetic pulses in virus-infected explants. Another promising avenue is integration with other biotechnologies, such as using gene-edited resistance in combination with physical treatments or priming plants with antiviral RNA interference triggers. By pursuing these avenues, electrotherapy (with or without MPT) can be refined into a reliable component of integrated virus-sanitization strategies for potatoes and other crops (Thanuja et al., 2025a).

Conclusion

The study demonstrated the effectiveness of electrotherapy for the elimination of viral infections in potatoes, in particular PVM, PVA and PLRV. The optimal mode of electrotherapy of *in vitro* potato plant cuttings from PVM is a current of 15-20mA for 20min. The most pronounced eliminating effect of electrotherapy from PVA was established when treating potato cuttings with a current of 20 mA for 30min. The eliminating effect of electrotherapy from PLRV persisted after 1 month of cultivation when treated with a current of 20mA for 30min. The studied electrotherapy modes were ineffective for PVX and PVS. For PLRV, no immediate post-treatment elimination was observed; however, a single regenerant remained PLRV-negative 30 days after treatment with 20mA for 30min, indicating a rare but possible delayed sanitation effect. It was found that prolonged exposure to electric current (over 10min) can stop plant morphogenesis. The healing effect was observed mainly in cuttings taken not from the apical part of the plant. These results confirm the potential of electrotherapy as a promising method for improving the health of potato planting material. Magnetic pulse treatment in the 8, 16 and 32Hz modes did not ensure the elimination of PVY, PLRV and PVM. Magnetic treatment at a frequency of 8Hz on the varieties Cerata and Colomba led, according to ELISA data, to a decrease in the concentrations of PVX and PVM viruses in potato tissues.

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