

Effects of acetic acid on plant responses to Tomato bushy stunt virus infection

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Abstract. Plant viral infections pose a serious challenge to agriculture and plant research, as they can cause significant yield losses and negatively impact plant growth. Unlike bacterial or fungal pathogens, plant viruses are not controlled by standard chemical pesticides once they have infected. As a result, researchers are increasingly interested in finding alternative ways to reduce viral infection or limit viral replication in plant tissues. One of the most promising areas of plant pathology is the study of inexpensive and environmentally friendly chemicals that can enhance plant resistance or inhibit viral infection processes. Chemicals that have generated interest in this area include organic acids. Acetic acid is an inexpensive organic acid that has been reported to promote stress adaptation and defense responses in plants. This study examined the effect of acetic acid on *Nicotiana benthamiana* infection with tomato bushy stunt virus (TBSV). Plants were treated with acetic acid solutions (5, 10, and 20 mM) by spraying the leaves and then infected with TBSV. These findings suggest that acetic acid may serve as an effective inducer of plant defense responses and could potentially enhance resistance against pathogen infection. Plants must cope with stress-related variations, such as oxidative stress, to survive. Catalase activity, an important indicator of antioxidant defense, was analyzed by native polyacrylamide gel electrophoresis. Virus-infected plants exhibited higher catalase activity than control plants, indicating activation of antioxidant responses during infection. In contrast, treatment with 5 mM acetic acid alone reduced catalase activity. When combined with virus infection, catalase activity

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increased, remaining higher than that of acetic acid-treated plants but lower than that of virus-infected plants. These results suggest that acetic acid modulates oxidative stress responses associated with TBSV infection and may contribute to improved redox homeostasis and antiviral defense in *N. benthamiana*.

Keywords: *Nicotiana benthamiana*, TBSV, acetic acid, Catalase, plants

Introduction

Plant viruses are important phytopathogens that cause significant losses in agricultural production worldwide by reducing both crop yield and quality [1]. Their genomes consist of single-stranded or double-stranded DNA or RNA molecules with different polarities, enclosed within a protein capsid [2]. Due to their limited coding capacity, plant viruses rely on the host cellular machinery to complete their infection cycle. Transmission of plant viruses occurs mainly through vectors, pollen, and seeds, although contaminated soil, water, and plant debris may also contribute to virus spread. The emergence of new viral species and variants, changes in agricultural practices, and the effects of global climate change continue to complicate the management of plant viral diseases [3].

Among the various plant viruses used in research, Tomato bushy stunt virus (TBSV) has become one of the most extensively studied experimental systems [4]. TBSV was first identified in tomato plants in 1935 and has subsequently been detected in numerous other plant species [5]. Depending on the host, infection can result in symptoms ranging from mild growth retardation and systemic mosaic to severe disease manifestations [6]. TBSV possesses a remarkably broad experimental host range, infecting more than 120 plant species from 20 different families, which makes it a valuable model for fundamental and applied virological studies [7]. In addition, TBSV has been successfully developed as a biotechnology platform for heterologous gene expression, functional genomics studies, and the delivery of genome-editing components [8]. TBSV belongs to the family Tombusviridae and produces non-enveloped icosahedral virions with T=3 symmetry. The viral particles are approximately 33 nm in diameter and consist of 180 coat protein subunits with a molecular mass of about 42 kDa [9]. Structurally, the virion contains approximately 17% ribonucleic acid and 83% protein. The viral genome is composed of a positive-sense single-stranded RNA molecule of approximately 4.8 kb that lacks both the 5' cap and the 3' poly(A) tail characteristic of eukaryotic messenger RNAs [10]. The TBSV genome contains five open reading frames (ORFs). ORF1 encodes a 33 kDa accessory replication protein (p33), while ORF2 encodes a 92 kDa RNA-dependent RNA polymerase (p92) produced through translational readthrough of the p33 stop codon. The remaining ORFs encode the coat protein (p41), a movement protein (p22), and a suppressor of virus-induced gene silencing (p19). These proteins collectively mediate viral replication, movement, encapsidation, and suppression of host antiviral defense mechanisms [6].

Nicotiana benthamiana is one of the most widely used model plants in plant biology and virology [11]. This species belongs to the Solanaceae family and is native to Australia [12]. Owing to its high susceptibility to numerous plant viruses, *N. benthamiana* has become a preferred experimental host for investigating virus-plant interactions [13]. The species is highly amenable to genetic transformation, transient protein expression, and virus-induced gene silencing, making it particularly suitable for studies of protein localization, protein-protein interactions, and functional genomics [14]. The combination of TBSV and *N. benthamiana* represents a powerful experimental system for studying viral replication, host-virus interactions, and plant defense

responses. Consequently, this model has become an indispensable tool in modern plant virology and biotechnology research [15].

Acetic acid (CH_3COOH) is a simple organic compound widely known as the main component of vinegar and has recently attracted considerable attention as a plant stress-protective agent. Numerous studies have demonstrated that exogenous application of acetic acid enhances plant tolerance to adverse environmental conditions through the modulation of physiological and biochemical processes. Acetic acid treatment promotes abscisic acid (ABA) accumulation, regulates stomatal aperture, reduces transpiration rates, and improves plant water status under stress conditions [16]. Furthermore, foliar application of acetic acid has been shown to increase plant survival under drought stress by reducing transpirational water loss without causing phytotoxic effects [17]. Recent studies also revealed that acetic acid alleviates the detrimental effects of drought, salinity, and heavy metal toxicity by enhancing photosynthetic performance, chlorophyll biosynthesis, nutrient-use efficiency, and antioxidant defense systems [18]. In addition, acetic acid induces the expression of the jasmonic acid biosynthesis gene *AOC3*, leading to increased jasmonic acid accumulation and activation of stress-responsive defense mechanisms [18]. These findings suggest that acetic acid may serve as an effective inducer of plant defense responses and could potentially enhance resistance against pathogen infection.

Plants must cope with stress-related variations, such as oxidative stress, to survive. Catalase (EC 1.11.1.6) is a tetrameric heme enzyme that metabolizes stress-induced reactive oxygen species and regulates their effects on cellular metabolism and activities [19]. CAT, found mostly in peroxisomes, catalyzes dismutation reactions without the need for a reductant [20].

CAT, initially refined and crystallized from high-purity bovine liver, has now been isolated and described from numerous sources, including plants [21]. CAT, an iron-containing enzyme, can be inhibited by cyanide. CATs from different sources have identical subunits, molecular weight, and prosthetic groups. The enzyme is a tetramer with four subunits of 54-59 kDa and a total molecular mass of around 240 kDa [20]. Small gene families typically encode plant CAT proteins. For instance, three members of the CAT family in *Arabidopsis* have distinct but relatively overlapping expression patterns in various tissues. Pollen and seeds are the main sources of CAT1 expression, green tissue is home to CAT2, the primary photorespiratory form of CAT, and vascular tissue and senescing organs are the main sources of CAT3 expression [22].

Catalase, a plant enzyme, plays an important part in plant defense mechanisms [22, 23]. Catalase is an antioxidant enzyme that aids in the conversion of hydrogen peroxide into water and oxygen [24]. Hydrogen peroxide is formed as a byproduct of many metabolic processes in plants and can be hazardous if not controlled. Catalase functions as a defensive mechanism by efficiently digesting H_2O_2 , preventing its buildup and reducing oxidative stress in plant cells. Catalase is also involved in the detoxification of various reactive oxygen species, which can help plants' overall antioxidant defense system. Catalase contributes to cellular homeostasis by scavenging and neutralizing ROS, as well as protecting plants from oxidative damage caused by both biotic and abiotic stressors [23].

Infection of *Nicotiana benthamiana* with Tomato bushy stunt virus increased hydrogen peroxide (H_2O_2) levels compared to mock-inoculated plants, suggesting an oxidative burst during the infection process [25]. Analysis of antioxidant enzyme activities demonstrated that virus infection boosted catalase (CAT) activity in *N. benthamiana* roots and leaves. Notably, two more CAT isoforms were activated in leaves after viral inoculation. Overall, these findings suggest that TBSV infection dramatically alters the activity of enzymes responsible for maintaining the equilibrium of reactive oxygen species buildup in plant tissues, indicating a coordinated antioxidant response to pathogen attack [26].

The present study investigated the potential effect of acetic acid on Tomato bushy stunt virus (TBSV) infection in *Nicotiana benthamiana* plants. Acetic acid was applied as an aqueous foliar spray at concentrations of 5, 10, and 20 mM. Since acetic acid has been reported to enhance plant stress tolerance through the modulation of physiological and biochemical processes associated with defense responses, it was hypothesized that its application could influence the development of viral infection. Therefore, the aim of this study was to evaluate whether exogenous acetic acid treatment affects the progression and spread of TBSV infection in *N. benthamiana* plants and to assess the plant response to viral challenge under different acetic acid concentrations.

Materials and research methods

Growth conditions

Nicotiana benthamiana plants were grown from seeds under controlled environmental conditions. Seeds were initially germinated in a common pot under dark conditions. After 72 h, the cover was removed, and seedlings were exposed to light. Seven days after sowing, the seedlings were transplanted individually into 250 mL pots containing approximately 110 g of universal soil supplemented with 0.8 g of vermiculite as a drainage material.

The substrate was enriched with an organic fertilizer containing essential macro- and micronutrients. The fertilizer contained 100 mg L⁻¹ total nitrogen (N), 50 mg L⁻¹ phosphorus (P₂O₅), 200 mg L⁻¹ potassium (K₂O), and 30 mg L⁻¹ magnesium (MgO). In addition, it contained iron (0.8–2 mg kg⁻¹), zinc (0.2–3 mg kg⁻¹), copper (3.0–5.0 mg kg⁻¹), manganese (8–40 mg kg⁻¹), molybdenum (0.1–0.4 mg kg⁻¹), and boron (0.4–1.6 mg kg⁻¹). The fertilizer had a moisture content below 60%, a humic compound content of 13%, and a pH ranging from 5.5 to 6.5.

Acetic acid solutions were prepared from glacial acetic acid. A 20 mM stock solution was obtained by dilution with distilled water and subsequently diluted to prepare 10 mM and 5 mM working solutions. Fifteen-day-old plants were treated daily with 5 mL of acetic acid solutions (5 mM, 10 mM, 20 mM) using a foliar spray application for seven consecutive days.

Plants were cultivated in a growth chamber under long-day conditions (16 h light/8 h dark) at 22–27°C and 75–80% relative humidity. Illumination was provided by lamps with spectral outputs of 2700 K and 6400 K arranged alternately. All plants were watered daily with 20 mL of distilled water. Thirty-day-old plants were used for subsequent experiments.

Plant virus infection

TBSV was mechanically injected into *Nicotiana benthamiana* plants that were one month old. Before inoculation, phosphate buffer and viral material were combined in a 1:1 ratio. A total of 100 µL of the inoculum was applied to each plant. For inoculation, the fifth and sixth leaves from the apical meristem were chosen. 50 µL of the inoculum was applied to each leaf. The rub method was used for mechanical inoculation. To help the virus enter the plant tissues, the inoculum was gently rubbed over the leaf surface using Celite as an abrasive. A week after infection, materials were collected for further research.

Plants were also inoculated by mechanically infiltrating the viral solution into leaf tissue. For this reason, a disposable syringe with no needle was utilized. The syringe tip was gently placed against the leaf's abaxial (bottom) surface, and 100 µL of viral suspension per plant was precisely injected using mild pressure. This allowed the suspension to penetrate the leaf mesophyll via stomatal openings and intercellular gaps. The infiltration was done to prevent causing severe mechanical injury to the leaf tissue. Treated leaves were visually inspected to ensure effective infiltration, which was indicated by small local darkening in the infiltrated region.

Agarose gel electrophoresis

Nucleic acids isolated from plant samples were analyzed using agarose gel electrophoresis, which also determined the presence of viral nucleic acids. This approach separates nucleic acids based on their size and allows for viewing under ultraviolet light following staining with an intercalating dye.

A 1% agarose gel was made by dissolving 0.6 g agarose in 60 mL of TAE buffer (Tris-Acetate-EDTA). The mixture was heated until the agarose had fully dissolved and the solution was clear. After cooling slightly, 3 μ L of ethidium bromide was added to the solution to see nucleic acids under UV light. The gel solution was poured onto a casting tray with a comb inserted to make wells, then allowed to harden at room temperature.

TAE buffer was utilized for both gel preparation and electrophoresis. The buffer provides appropriate ionic strength and keeps the pH steady during nucleic acid separation. Before loading, samples were mixed with loading dye to improve visibility and density. For each sample, 5 μ L of plant extract was combined with 1 μ L of purple loading dye and injected into the agarose gel. Electrophoresis was done in TAE buffer until the nucleic acids were sufficiently separated. Following electrophoresis, the gel was examined under ultraviolet light to detect nucleic acid bands, which allowed the presence and relative quantity of viral nucleic acids in the samples to be estimated.

Determination of nucleic acid concentration and purity

A NanoDrop spectrophotometer was used to determine the concentration and assess the purity of nucleic acids isolated from plant samples. Prior to measurements, the measurement pedestal was cleaned by applying 3 μ L of nuclease-free deionized water, and any remaining liquid was carefully wiped away with a lint-free lab tissue. The instrument was calibrated, and a baseline (blank) measurement was performed using the same nuclease-free water. For the analysis of each sample, a 2 μ L aliquot of the plant extract was loaded onto the measurement pedestal. The software recorded optical density values at wavelengths of 260 nm and 320 nm to calculate the quantitative nucleic acid content and perform background scattering correction.

Preparation of samples for experiment

To prepare samples, fresh leaves of seven-day-old seedlings were harvested and immediately processed to prevent enzymatic degradation. Leaf material was thoroughly homogenized using a pre-cooled mortar and pestle with the addition of extraction buffer. The extraction buffer was freshly prepared and contained 250 mM sucrose, 3 mM EDTA (pH 8.3), 250 mM Tris-HCl, L-cysteine, molybdenum solution, dithiothreitol (DTT), and DDW. This composition was chosen to stabilize proteins and enzymes, prevent oxidation, and maintain the structural integrity of biomolecules during homogenization. The homogenate was transferred to pre-cooled centrifuge tubes and centrifuged at 10,000 rpm for 25 minutes at 4°C. Centrifugation at low temperature was used to reduce the risk of protein denaturation and enzymatic activity. After centrifugation, the supernatant, which contained soluble proteins and metabolites, was gently separated from the pellet, which consisted mainly of cellular debris and intact tissue. The obtained supernatants were immediately used for further biochemical analysis. Protein concentration was measured using the Bradford method.

Bradford protein assay

Protein concentration was determined in a 96-well cell culture plate using the Bradford assay. Samples were analyzed in technical triplicates across three consecutive rows of the plate, with each well containing 20 μ L of the diluted sample and 200 μ L of Bradford reagent [27]. The

absorbance was measured at 595 nm using a Biochrom Asys Expert 96 microplate spectrophotometer. This normalization procedure was employed to standardize the protein concentrations across all samples prior to subsequent enzymatic activity assays.

Determination of catalase activity in gel

Denaturing electrophoresis was performed using a 7,5% vertical polyacrylamide gel [28]. For 5 minutes, the gels were submerged in a solution containing 0.03% H_2O_2 . Two falcons were created: the first falcon contained 0.6 g of iron (III) chloride per 30 ml of distilled water, whereas the second falcon contained 0.6 g of potassium ferricyanide (III) per 30 ml of distilled water. The contents of the two falcons were added to the gel and thoroughly mixed for 1 minute. Finally, the gel was carefully washed with distilled water [29].

Statistical analysis

All experiments were repeated at least three times to confirm the reliability of the results. Data from three independent replicates were converted to numerical values ($\pm$ SD), and *ImageJ* was used to quantify enzyme activity intensity.

Results and Discussion

Optimizing the experimental design. At the beginning of the study, it was required to select the best experimental design for the timing of acetic acid treatment in relation to viral infection. Two options were considered: treating plants with acetic acid before viral infection or treating after infection. Two pilot plantings were undertaken. Based on preliminary findings and previously published research, acetic acid doses of 5 mM, 10 mM, and 20 mM were chosen for testing. These doses were chosen since they did not kill plants while eliciting noticeable physiological reactions. The following experimental groups were set up: K (untreated control), V (virus-infected plants without acetic acid treatment), 5 (5 mM acetic acid), 5V (5 mM acetic acid+virus TBSV), 10 (10 mM acetic acid), 10V (10 mM acetic acid+virus TBSV), 20 (20 mM acetic acid), and 20V (20 mM acetic acid+virus TBSV). In the first experiment, plants were injected with the virus and treated with acetic acid by foliar spray (Figure 1 A). In the second pilot experiment, plants were treated with acetic acid before viral injection (Figure 1 B). The second strategy revealed that acetic acid therapy after viral infection did not increase plant survival. Following infection, a considerable number of plants perished, leaving very little plant material available for further study. Because of the low survival rate and inadequate viable plant material, this experimental technique was deemed insufficient for future study.

As a result, the first experimental design (viral inoculation followed by acetic acid treatment) was chosen for further experiments.

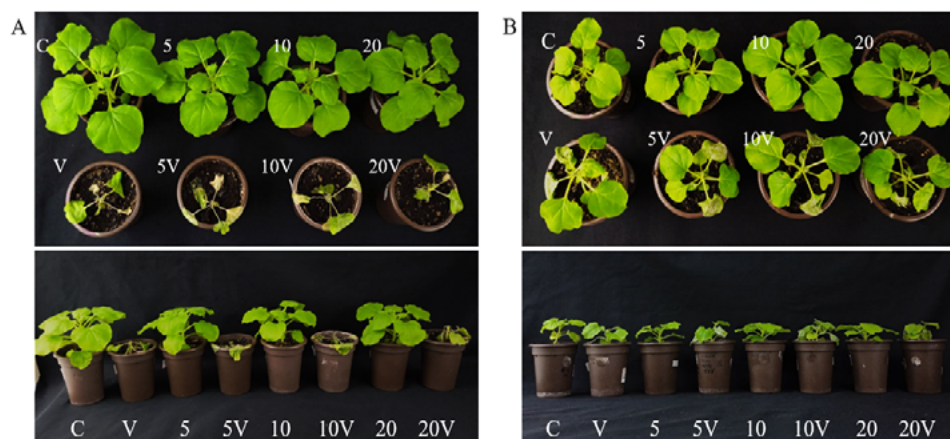


Figure 1. *Nicotiana benthamiana* plants infected with virus and then treated with acetic acid (A) and plants treated with acetic acid and then virus (B), top and side views. C – control plants; V – virus-infected plants; 5, 10 and 20 – plants treated with 5, 10 and 20 mM acetic acid, respectively; 5V, 10V and 20V – virus-infected plants treated with the corresponding acetic acid concentrations

Isolation and verification of tomato bushy stunt virus. A hydroxyapatite column was used to purify viral material extracted from infected plant tissue in order to eliminate biological impurities and produce fractions enriched in viral particles. Because hydroxyapatite chromatography can selectively bind proteins and nucleic acids based on how they interact with calcium phosphate, it was used to purify biological macromolecules. A hydroxyapatite column was filled with the crude plant extract containing viral particles, which then flowed through the matrix. While fractions containing virus particles were gathered in different tubes, contaminants such as plant proteins and cellular debris were partially retained by the column material throughout the procedure. 3 fractions in all were gathered in 1.5 mL Eppendorf microcentrifuge tubes.

The spectrophotometric analysis showed that the collected fractions' nucleic acid concentrations varied. Following blank calibration with nuclease-free water, measurements were made. Nucleic acid concentration was automatically determined by the instrument software using the standard formula based on absorbance at 260 nm. Several fractions had far greater nucleic acid contents than the rest, according to the research, suggesting that these samples were enriched with viral genetic material. Thus, these fractions were chosen for additional examination and testing. Picture 2 shows the absorbance of viral material as detected by a spectrophotometer. Table 1 illustrates the concentration of nucleic acids in viral material.

Table 1.

Concentration of nucleic acids in viral material

Sample	Nucleic acid concentration (ng/ μ L)
Control	580
1	1593
2	2056
3	1887

Then, agarose gel electrophoresis was used to assess the presence of viral nucleic acids in the 4 samples (Figure 2). Nucleic acids segregated by size may be seen. The spectrophotometric results were supported by the acquired electrophoretic profiles, which verified the presence of nucleic acids in the chosen samples. It should be mentioned that while agarose gel electrophoresis makes viral nucleic acids visible, it does not directly detect viral particles. Thus, the presence of viral RNA linked to the virus-containing samples was revealed by the presence of nucleic acid bands in the examined fractions.

The lanes in the gel showed visible nucleic acid bands, indicating the presence of nucleic acids in the examined materials. The most visible bands were found in lanes 1, 2, and 3, indicating that these samples contained more nucleic acids than the rest. The bands in lanes 1-3 were found in identical places on the gel, indicating that the nucleic acids in these samples were of similar size. Samples 2 and 3 were used to inoculate the plants.



Figure 2. Agarose gel electrophoresis of viral material isolated from *Nicotiana benthamiana*

The fractions with the highest concentration of viral nucleic acids (samples 2 and 3) were used to inoculate two *Nicotiana benthamiana* plants in order to verify that the recovered viral material remained physiologically active. To confirm that the virus preparation was infectious, mechanical inoculation was carried out. The plants were observed for virus-related symptoms after inoculation (Figure 3A and 3B). The development of distinctive symptoms demonstrated a successful infection and verified the virus preparation's continued infectiousness.

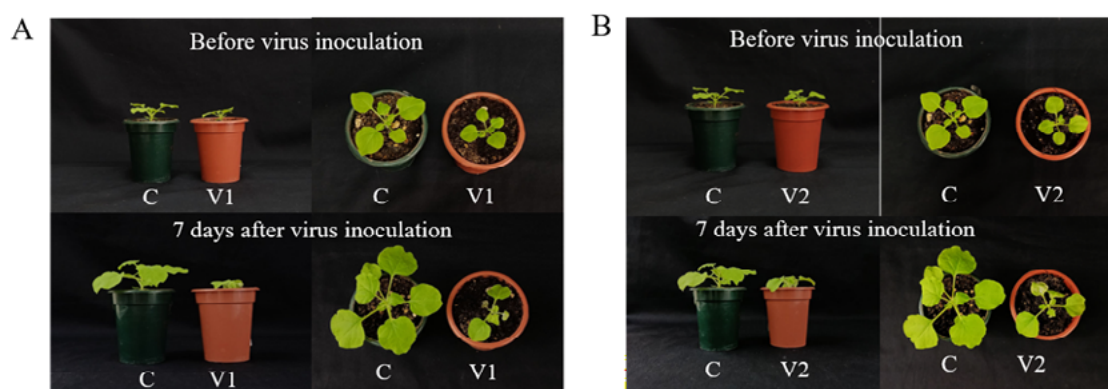


Figure 3. *Nicotiana benthamiana* plants infected with a syringe (A) and mechanically (B) before and 7 days after infection, side and top views. C – control plants; V1 – plants infected with a syringe; V2 – plants infected mechanically

Agarose gel electrophoresis was used to examine plant samples in order to confirm viral replication in the infected plants (Figure 4). These findings showed that physiologically active viruses that may infect *Nicotiana benthamiana* plants and multiply within plant tissues were present in the chosen fractions.

The absence of detectable viral nucleic acids in healthy plant tissue was demonstrated by the electrophoretic analysis, which revealed that the control sample (K) had no visible nucleic acid bands. On the other hand, the samples taken from plants infected with the virus showed distinct nucleic acid bands. In comparison to the control sample, these bands were noticeably stronger, indicating that the infected plant material contained viral nucleic acids. Both inoculated plants were successfully infected and had measurable amounts of viral genetic material, as shown by the comparable band patterns shown in lanes V1 and V2.



Figure 4. Agarose gel of test plants for virulence testing. C – control plants; V1 – plants infected with a syringe; V2 – plants infected mechanically

Symptoms of Nicotiana benthamiana exposed to virus and acetic acid. The visual condition of plants treated with various concentrations of acetic acid was assessed and compared to healthy control plants and virus-infected plants that were not treated. As indicated in Figure 5, the healthy control plants (K) had regular growth and well-developed green leaves. In contrast, virus-infected plants that were not treated (V) demonstrated evident indications of infection, such as reduced growth and leaf deformation.

Plants treated with acetic acid at doses of 5 mM and 10 mM showed no significant obvious alterations from untreated infected plants. The general plant morphology and symptom development appeared reasonably similar, implying that these doses did not cause significant observable changes in plant condition. However, plants treated with 20 mM acetic acid appeared to be slightly healthier than other infected plants. These plants had slightly improved leaf development and overall growth, which could imply a favorable effect of greater acetic acid concentration on plant condition during viral infection. Overall, acetic acid treatment did not result in significant obvious changes in plant shape, while plants treated with 20 mM acetic acid appeared slightly healthier than the other infected plants.



Figure 5. *Nicotiana benthamiana* plants exposed to acetic acid and a virus, top and side views. C – control plants; V – virus-infected plants; 5, 10 and 20 – plants treated with 5, 10 and 20 mM acetic acid, respectively; 5V, 10V and 20V – virus-infected plants treated with the corresponding acetic acid concentrations

When the leaves were examined attentively, tiny damaged regions were seen on plants treated with 20 mM acetic acid (Figure 6). They are highlighted in red in the image. These appeared as small, pale, dry patches on the leaf surface, similar to minor burn symptoms. Such symptoms are consistent with chemical phytotoxicity, which is frequently seen as small burnt or bleached areas on leaves following chemical application.

One probable reason for this effect is the unequal dispersion of acetic acid solution over the leaf surface. Some droplets may have collected while spraying, resulting in bigger drops that remained on the leaves for prolonged periods of time. Because acetic acid operates as a contact chemical, damaging plant tissues immediately at the site of contact, continuous exposure in certain locations may result in small necrotic or dehydrated spots on the leaves.



Figure 6. The effect of treating *Nicotiana benthamiana* leaves with a 20 mM acetic acid spray

Catalase activity. Catalase activity was measured in plant samples after various treatments using native polyacrylamide gel electrophoresis. The electrophoretic pattern of catalase activity is shown in Figure 7. Catalase activity bands were found in all of the materials tested, as shown on the gel. The control sample (C) exhibited a distinct band matching catalase activity in healthy plants. The band intensity in the virus-infected sample (TBSV) was higher than in the control, showing that catalase activity increased during viral infection. The increase in catalase activity in infected plants is likely due to increased formation of reactive oxygen species (ROS), in particular hydrogen peroxide (H_2O_2), which is a common component of plant defense responses against pathogens [30-32]. Viral infection often induces oxidative stress, resulting in elevated ROS accumulation. Catalase plays a crucial role in detoxifying H_2O_2 , thereby protecting cellular structures from oxidative damage [33]. Therefore, the stronger catalase activity observed in virus-infected plants may reflect an adaptive response aimed at maintaining cellular redox homeostasis.

Plants treated alone with acetic acid produced weaker bands than both the control and virus-infected samples. The 5 mM treatment (5) showed a weak band, indicating lower catalase activity. A similar trend was seen for the 10 mM (10) and 20 mM (20) treatments, with the band intensity being quite low. This suggests that acetic acid reduced endogenous ROS formation, thereby reducing the need for H_2O_2 scavenging by catalase. It is also possible that low concentrations of acetic acid may function as signaling molecules capable of inducing stress adaptation mechanisms without significant oxidative damage. Interestingly, when acetic acid treatment was combined with viral infection (5V, 10V and 20V), catalase activity increased compared to the corresponding treatments with acetic acid alone. This result indicates that viral infection remained a strong inducer of antioxidant responses even in the presence of acetic acid. The increased catalase activity observed with the combined treatment may be due to the activation of defense mechanisms triggered by pathogen invasion, leading to increased ROS production and subsequent induction of antioxidant enzymes. At the same time, catalase activity in infected plants treated with acetic acid did not appear to exceed that observed with virus treatment alone, suggesting that acetic acid may partially mitigate the oxidative stress associated with viral infection. This effect may be due to the activation of plant defense responses by acetic acid, allowing plants to more effectively respond to pathogen-induced stress while limiting excessive ROS accumulation. Therefore, the observed pattern of catalase activity supports the hypothesis that acetic acid modulates the antioxidant response during viral infection and helps maintain the redox balance in infected plants. The native PAGE data show that catalase activity increased in virus-infected plants compared to untreated plants, whereas treatment with acetic acid alone reduced enzyme activity. However, catalase activity was generally higher in virus-infected plants treated with acetic acid than in plants treated just with acetic acid.



Figure 7. Native PAGE of catalase activity in *Nicotiana benthamiana* leaves after various treatments. C – control plants; V – virus-infected plants; 5, 10 and 20 – plants treated with 5, 10

and 20 mM acetic acid, respectively; 5V, 10V and 20V – virus-infected plants treated with the corresponding acetic acid concentrations

Using *ImageJ* software, the activity was converted into a percentage and is shown in Figure 8. The proportion of activity differed amongst the examined samples based on virus infection and acetic acid treatment.

The control sample had an activity level of 18.98%. In contrast, the virus-infected sample without treatment had a higher value of 22.34%, showing an increase in activity in response to viral infection.

Treatment with 5 mM acetic acid (5) yielded a much lower value (7.15%) than the control. When virus infection was paired with this medication (5V), activity increased to 11.87%, but it remained lower than the control value. When comparing pairs 5 and 5V, virus-infected plants outperformed plants treated just with acetic acid.

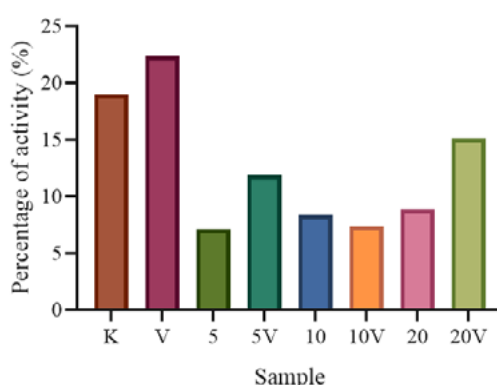


Figure 8. Percentage activity of catalase. K – control plants; V – virus-infected plants; 5, 10 and 20 – plants treated with 5, 10 and 20 mM acetic acid, respectively; 5V, 10V and 20V – virus-infected plants treated with the corresponding acetic acid concentrations

These results indicate that viral infection promotes catalase activation as part of the plant antioxidant response, whereas treatment with acetic acid alone reduces catalase activity, likely due to reduced ROS accumulation. The intermediate catalase activity observed with 5V treatment suggests that acetic acid may modulate virus-induced oxidative stress and contribute to the maintenance of cellular redox homeostasis. This effect is consistent with the proposed role of acetic acid as a priming agent that enhances adaptation to stress while preventing excessive activation of oxidative stress responses.

Conclusion

In conclusion, this study demonstrated that acetic acid influences the antioxidant response of *Nicotiana benthamiana* plants during infection with tomato bushy stunt virus (TBSV). Analysis of catalase activity revealed that viral infection stimulates the antioxidant defense system, as evidenced by increased catalase activity compared to healthy control plants. This response is likely related to increased formation of reactive oxygen species and the need to maintain cellular redox balance under pathogen-induced stress. Treatment with acetic acid alone resulted in a decrease in catalase activity, suggesting that acetic acid did not induce severe oxidative stress and may contribute to maintaining a more balanced physiological state of the plants. When acetic

acid treatment was combined with TBSV infection, catalase activity increased compared to plants treated with acetic acid but remained lower than in virus-infected plants without treatment. These results indicate that acetic acid modulates the response to oxidative stress induced by viral infection and may partially mitigate the negative consequences of pathogen-induced accumulation of reactive oxygen species. Overall, the results indicate that acetic acid has the potential to act as a modulator of plant defenses, contributing to improved redox homeostasis during viral infection. Further research is needed to elucidate the molecular basis of these responses and evaluate the potential of acetic acid as an environmentally friendly agent for enhancing plant resistance to viral infections.

Author Contributions

M.B., M.M., and N.N. – conceptualization; **M.M., K.Zh., A.M., A.A.** – data curation; **M.B., M.M., and A.M.** – formal analysis; **M.B., M.M., and A.Zh., A.A., N.N.** – investigation; **M.B., A.K., S.Zh. and Zh.M.** – methodology; **M.B.** – visualization; **M.B., M.M. and A.B.** – writing – original draft; **M.B., A.M., K.Zh., S.Zh., A.B., A. Zh., M.M., and Zh.M., M.M.** – writing – review & editing; **M.M., and Zh.M.** – project administration; **M.B., K.Zh., N.N. and Zh.M.** – supervision; **N.N., Zh.M.** – funding acquisition and resources. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Compliance with ethical standards

This article does not contain a description of studies performed by the authors involving people or using animals as objects.

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Сірке қышқылының қызанақтың ергежейлігі вирустық инфекциясымен зақымдаудағы өсімдіктердің реакциясына әсері

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Аңдатпа. Өсімдіктердің вирустық инфекциялары ауыл шаруашылығы мен өсімдік зерттеулеріне үлкен қауіп төндіреді, себебі олар өнімнің айтарлықтай жоғалуына және өсімдіктердің өсуіне кері әсер етуі мүмкін. Бактериялық немесе саңырауқұлақ патогендерінен айырмашылығы, өсімдік вирустары инфекциядан кейін стандартты химиялық пестицидтермен бақыланбайды. Сондықтан, вирустық инфекцияны азайтудың

немесе өсімдік тіндерінде вирустың көбеюін шектеудің балама жолдарын табуға бағытталған зерттеулер барған сайын маңызды болып келеді. Фитопатологияның ең перспективалы салаларының бірі вирусқа қарсы әсері бар арзан және экологиялық таза химиялық заттарды зерттеу. Органикалық қышқылдар ерекше қызығушылық тудырады. Сірке қышқылы өсімдіктердегі стресс жағдайларына бейімделу мен қорғаныс реакцияларын күшейтуге қабілетті, кең қолжетімді органикалық қышқылдардың бірі ретінде қарастырылады. Бұл зерттеу сірке қышқылының *Nicotiana benthamiana* инфекциясына қызанақ бұтасының стресті вирусымен (TBSV) әсерін зерттейді. Өсімдіктер сірке қышқылының ерітінділерімен (5, 10 және 20 мМ) жапырақтарға бүрку арқылы өңделді, содан кейін TBSV жұқтырылды. Бұл нәтижелер сірке қышқылының өсімдіктердің қорғаныс реакцияларының тиімді индукторы ретінде қызмет ете алатынын және патогендік инфекцияға төзімділікті арттыра алатынын көрсетеді. Өсімдіктер аман қалу үшін тотығу стресі сияқты стресстік өзгерістерге төтеп беруі керек. Антиоксиданттық қорғаныстың маңызды көрсеткіші болып табылатын каталаза белсенділігі нативті полиакриламидті гель электрофорезі арқылы талданды. Вирус жұқтырған өсімдіктерде каталаза белсенділігі бақылау өсімдіктеріне қарағанда жоғары болды, бұл инфекция кезінде антиоксиданттық реакциялардың белсендірілгенін көрсетеді. Керісінше, тек 5 мМ сірке қышқылымен емдеу каталаза белсенділігін төмендетті. Вирустық инфекциямен біріктірілген кезде каталаза белсенділігі артты, сірке қышқылымен өңделген өсімдіктерге қарағанда жоғары болды, бірақ тек вирус жұқтырған өсімдіктерге қарағанда төмен. Алынған нәтижелер сірке қышқылының TBSV инфекциясынан туындайтын тотығу стресіне жауап реакцияларын модуляциялайтынын және *Nicotiana benthamiana* өсімдіктерінде тотығу-тотықсыздану гомеостазын тұрақтандыруға және вирусқа қарсы қорғаныс механизмдерін күшейтуге әсер етуі мүмкін екенін көрсетеді.

Түйін сөздер: *Nicotiana benthamiana*, TBSV, сірке қышқылы, каталаза, өсімдіктер

Влияние уксусной кислоты на реакцию растений на заражение вирусом карликовости томата

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Аннотация. Вирусные инфекции растений представляют собой серьезную угрозу для сельского хозяйства и научных исследований, поскольку они могут вызывать значительные потери урожая и негативно влиять на рост культур. В отличие от бактериальных или грибковых патогенов, вирусы растений не контролируются стандартными химическими пестицидами после заражения. В результате все более актуальными являются исследования направленные на поиск альтернативных способов снижения вирусной инфекции или ограничения репликации вирусов в тканях растений. Одним из наиболее перспективных направлений фитопатологии является изучение недорогих и экологически чистых химических веществ, обладающих антивирусными эффектами. Так особый интерес представляют органические кислоты. Уксусная кислота это самая доступная органическая кислота, которая, как сообщается, способствует адаптации к стрессу и защитным реакциям у растений. В этом исследовании изучается влияние уксусной кислоты на заражение *Nicotiana*

benthamiana вирусом кустистой карликовости томата (TBSV). Растения обрабатывались растворами уксусной кислоты (5, 10 и 20 мМ) путем опрыскивания листьев, а затем инфицировались TBSV. Эти результаты позволяют предположить, что уксусная кислота может служить эффективным индуктором защитных реакций растений и потенциально повышать устойчивость к заражению патогенами. Растения должны справляться со стрессовыми изменениями, такими как окислительный стресс, чтобы выжить. Активность каталазы, важный показатель антиоксидантной защиты, анализировали методом электрофореза в нативном полиакриламидном геле. У растений, инфицированных вирусом, активность каталазы была выше, чем у контрольных растений, что указывает на активацию антиоксидантных реакций во время инфекции. Напротив, обработка только 5 мМ уксусной кислотой снижала активность каталазы. В сочетании с вирусной инфекцией активность каталазы увеличивалась, оставаясь выше, чем у растений, обработанных уксусной кислотой, но ниже, чем у растений, инфицированных вирусом. Эти результаты позволяют предположить, что уксусная кислота модулирует реакции окислительного стресса, связанные с инфекцией TBSV, и может способствовать улучшению окислительно-восстановительного гомеостаза и противовирусной защиты у *Nicotiana benthamiana*.

Ключевые слова: *Nicotiana benthamiana*, TBSV, уксусная кислота, каталаза, растения

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