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Treatment Persistence and Resistance Monitoring in Bacteriophage Control of Bacterial Plant Diseases

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مراقبة استمرارية العلاج ومقاومة البكتيريا في مكافحة الأمراض البكتيرية النباتية باستخدام العاثيات

إسماعيل مصباح الفار
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Abstract:
Bacterial plant diseases reduce crop quality and threaten food production. Bacteriophages are viruses that infect bacteria and may support disease management. Their value depends on two linked questions. First, do active phages remain where protection is needed? Second, do target bacteria remain sensitive after exposure? This narrative review examines published experiments on phage persistence and bacterial resistance in plant disease control. It draws on studies involving tomato, rice, apple, pear, and cherry. The evidence includes laboratory work, plant experiments, and orchard trials. Tomato studies show that sunlight can shorten phage survival on leaf surfaces. Protective formulations improved persistence in some experiments, although benefits varied across plant systems. A rice experiment found smaller lesions after phage treatment than in untreated plants. An apple study reported disease reductions that differed greatly among locations and years. In cherry orchards, phages remained detectable longer when the bacterial host was present. However, detection did not ensure lasting bacterial suppression. Resistance findings also depended on the experimental setting. One tomato study found frequent resistance in laboratory cultures but little evidence of its emergence inside leaves. Other work documented existing variation and cross-resistance among fire blight bacteria. These results support joint assessment of phage activity, bacterial sensitivity, and disease outcomes. They also show that laboratory findings cannot predict field performance alone. More long-term, multi-location studies are needed before reliable predictions can be made across crops.

Keywords : bacteriophage; bacterial plant disease; treatment persistence; phage resistance; biological control; field monitoring.

الملخص:
تُقلل الأمراض البكتيرية التي تُصيب النباتات من جودة المحاصيل وتُهدد الإنتاج الغذائي. تُعد العاثيات البكتيرية فيروسات تُصيب البكتيريا، وقد تُساهم في إدارة الأمراض. وتعتمد أهميتها على سؤالين مترابطين: أولًا، هل تبقى العاثيات النشطة في المناطق التي تحتاج إلى الحماية؟ ثانيًا، هل تبقى البكتيريا المستهدفة حساسة بعد التعرض لها؟ يستعرض هذا البحث السردي التجارب المنشورة حول استمرار العاثيات ومقاومة البكتيريا في مكافحة أمراض النبات. ويستند إلى دراسات شملت الطماطم والأرز والتفاح والكمثرى والكرز. وتشمل الأدلة أعمالًا مخبرية وتجارب نباتية وتجارب في البساتين. تُظهر دراسات الطماطم أن ضوء الشمس يُمكن أن يُقلل من بقاء العاثيات على أسطح الأوراق. وقد حسّنت التركيبات الواقية من استمرار العاثيات في بعض التجارب، على الرغم من اختلاف الفوائد باختلاف أنواع النباتات. ووجدت تجربة على الأرز آفات أصغر حجمًا بعد المعالجة بالعاثيات مقارنةً بالنباتات غير المعالجة. وأفادت دراسة على التفاح بانخفاضات في الأمراض اختلفت اختلافًا كبيرًا بين المواقع والسنوات. في بساتين الكرز، ظلت العاثيات قابلة للكشف لفترة أطول عند وجود البكتيريا المضيفة. ومع ذلك، لم يضمن الكشف عنها قمعًا دائمًا للبكتيريا. كما اعتمدت نتائج المقاومة على بيئة التجربة. أظهرت إحدى الدراسات على الطماطم وجود مقاومة متكررة في المزارع المختبرية، ولكن لم يُرصد سوى القليل من الأدلة على ظهورها داخل الأوراق. ووثّقت دراسات أخرى وجود تباين ومقاومة متبادلة بين بكتيريا اللفحة النارية. تدعم هذه النتائج التقييم المشترك لنشاط العاثيات،

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وحساسية البكتيريا، ونتائج المرض. كما تُظهر أن نتائج المختبر وحدها لا تكفي للتنبؤ بالأداء الحقلي. لذا، ثمة حاجة إلى مزيد من الدراسات طويلة الأمد في مواقع متعددة قبل التوصل إلى تنبؤات موثوقة على مستوى المحاصيل.

الكلمات المفتاحية: العاثيات البكتيرية؛ أمراض النبات البكتيرية؛ استمرار العلاج؛ مقاومة العاثيات؛ المكافحة البيولوجية؛ الرصد الميداني.

1. Introduction

Bacterial plant diseases damage leaves, flowers, stems, fruits, and roots. Their effects range from visible spots to severe wilting and plant death. Some infections reduce market quality before total yield falls. Others spread rapidly through orchards or production fields (Buttimer et al., 2017).

Fire blight is an example of a serious bacterial disease in apple and pear. Its causal bacterium, *Erwinia amylovora*, can damage blossoms and young shoots. Figure 1 shows its scorched appearance on an apple branch. Bacterial spot of tomato and bacterial blight of rice present different challenges. Their pathogens occupy different plant tissues and production environments (Jain et al., 2023; Iriarte et al., 2007).



Figure 1 Fire blight symptoms on an apple branch. Photograph by Peggy Greb, USDA Agricultural Research Service.

Growers use several measures to limit bacterial diseases. These include resistant planting material, sanitation, disease forecasting, and approved products. Yet available options differ among crops and countries. Some bacterial populations also resist particular antibiotics or other bactericides (Gdanetz et al., 2024). These pressures have increased interest in biological control. Bacteriophages, often called phages, are viruses that infect bacteria. A suitable phage can enter a susceptible bacterium and produce new phage particles. Some phages then rupture the cell. Figure 2 shows phages attached to bacteria in an electron micrograph. That image is illustrative and does not show a crop pathogen.

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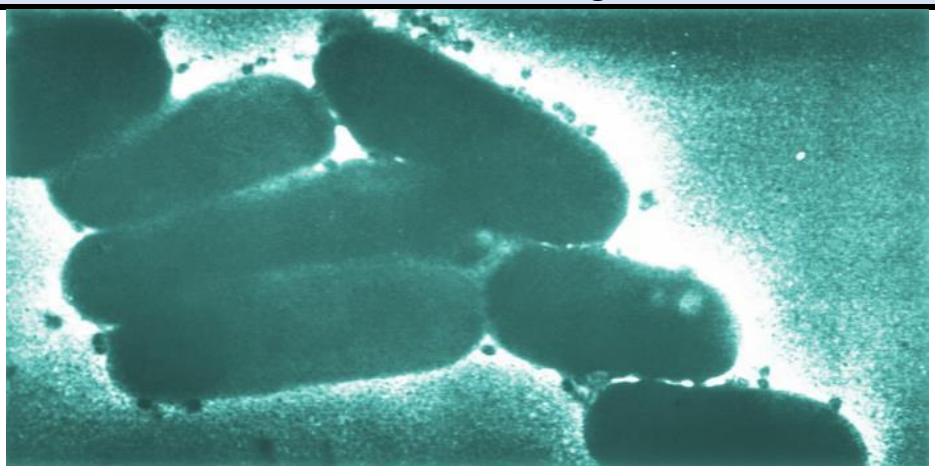


Figure 2: Phages attached to coliform bacteria in an electron micrograph. This is a general illustration, not a plant-disease experiment. Credit: CDC and Andrew Fodor.

Phages may target particular bacterial species or strains. This selectivity can limit effects on unrelated bacteria. However, selectivity can also leave some disease-causing strains uncontrolled. The outcome depends on the match between each phage and local bacterial populations (Schnabel & Jones, 2001).

Two linked difficulties deserve attention. Active phages may disappear from treated plant surfaces before the disease risk ends. Meanwhile, some target bacteria may tolerate or resist infection. These problems can occur together, and either can weaken disease control. A clear diagnosis requires evidence on both processes (Iriarte et al., 2007; Knecht et al., 2022).

This paper reviews published evidence on treatment persistence and phage resistance. It compares laboratory, plant, and field findings. It also considers how researchers can interpret disease outcomes alongside these measurements. The paper uses published secondary information and presents no new experiment.

2 Background

2.1 What persistence means

Persistence describes the continued presence of active phage after treatment. In these studies, activity means the phage retains the ability to infect a suitable bacterium. Detectable genetic material alone does not establish infectivity. Published studies use different measures, so their values require careful comparison (Iriarte et al., 2012; Papp-Rupar et al., 2025).

The useful duration of a treatment is not fixed by detection alone. A phage may remain detectable at levels too low to affect disease. It may also survive in a place where few target bacteria occur. Conversely, an early reduction in bacteria may benefit a crop after phage counts fall. Disease severity and active phage counts therefore answer different questions (Balogh et al., 2018).

A phage population can decline or increase after treatment. Environmental damage may lower activity. Multiplication depends on the presence of suitable bacterial hosts. Thus, measured persistence can reflect survival, multiplication, movement, and sampling differences. The contribution of each process is not always known (Papp-Rupar et al., 2025).

2.2 What resistance means

Phage resistance describes a reduced ability of a phage to infect or suppress a bacterium. A bacterial population may already contain strains that differ in sensitivity. Resistance may also appear after exposure. These explanations must not be treated as identical without evidence (Schnabel & Jones, 2001).

Resistance can be temporary or stable in a particular experimental setting. It can affect one phage or several phages. Cross-resistance occurs when reduced sensitivity extends to other

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phages. A mixture of phages is therefore not automatically protected against resistance (Knecht et al., 2022).

A resistant bacterium does not necessarily become more harmful. Resistance may change growth or disease-causing ability, but outcomes vary. Results from a single phage and host combination cannot establish a universal rule. The plant environment can also change whether resistance provides an advantage (Hernandez & Koskella, 2019).

3 Materials and Methods

3.1 Review design

This paper is a narrative review of published secondary evidence. Searches used PubMed, journal websites, and web search results available through 29 October 2026. Search terms combined bacteriophage, plant disease, persistence, resistance, field, tomato, rice, and fire blight. Studies were selected for relevance to the research question and availability of identifiable results.

Priority was given to primary studies with plant, greenhouse, or field observations. Laboratory studies were included when they explained resistance or sensitivity. Reviews supplied background and helped identify primary sources. The selected evidence covers tomato, rice, apple, pear, and cherry systems.

This was not a systematic review or a meta-analysis. No complete database search, screening count, or formal risk-of-bias score was produced. Reported values retain the measurements and comparisons from their original studies. No new patient, field, or laboratory data were collected.

3.2 Evidence extraction and interpretation

For each selected study, the review noted the crop, pathogen, setting, and main outcome. It distinguished phage detection from bacterial suppression and plant disease. It also recorded whether resistance was observed, absent, or unmeasured. Table 1 compares selected examples.

Table 1 Selected studies and their main contributions

Study	Crop and setting	Relevant finding
Iriarte et al. (2007)	Tomato; leaf and field	Sunlight reduced active phage on foliage.
Balogh et al. (2018)	Tomato; laboratory and greenhouse	Laboratory measures poorly predicted disease control.
Jain et al. (2023)	Rice; pot experiment	Phage-treated leaves had shorter lesions.
Gdanetz et al. (2024)	Apple; multiple field sites	Control varied among locations and years.
Papp-Rupar et al. (2025)	Cherry; leaves and orchard	Phage detection persisted with host bacteria.
Hernandez and Koskella (2019)	Tomato; culture and leaf tissue	Resistance differed between experimental settings.
Knecht et al. (2022)	Fire blight bacterium; laboratory	Cross-resistance affected some other phages.

Results were discussed separately when measurements or experimental settings differed. Percentage reductions were not pooled across studies. Study photographs and original graphics are identified by their source. New charts in this paper reproduce published summary values without adding observations.

4 Results from Published Experiments

4.1 Sunlight and persistence on tomato leaves

Iriarte et al. (2007) examined factors that influence phage survival on tomato foliage. Their experiments considered sunlight, temperature, drying, and exposure to copper. Ultraviolet light was a major cause of declining phage activity. Some tested formulations reduced the damage under their conditions.

The same study showed that environmental exposure could affect disease control. The authors linked ultraviolet damage to weaker activity against bacterial spot. A treatment that begins with active phage may therefore lose effectiveness after exposure. Yet the size of this loss depends on the environment and formulation.

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Earlier tomato research also compared formulated and unformulated phages. Balogh et al. (2003) reported better persistence and disease control with some formulations. Their results covered greenhouse and field conditions. These observations show potential, but they do not prove every formulation works equally well.

A formulation can influence more than survival on a leaf. It may affect the way a phage reaches bacteria. It may also interact with the plant surface or other treatment materials. The measured disease response remains necessary alongside any persistence measurement. Different crops may respond differently to the same type of protective material (Jain et al., 2023).

4.2 Movement and persistence within tomato plants

Iriarte et al. (2012) studied phage persistence in tomato roots and other tissues. The researchers detected phages in roots, stems, and leaves. Reported levels were generally lower in stems and leaves than in roots. The findings suggest that location matters when persistence is interpreted. The study also examined disease control in a bacterial wilt system. Responses depended on the timing of treatment relative to infection. This was an experimental result rather than a universal treatment schedule. The work did not establish equal access to every infected tissue.

A separate tomato study evaluated eight phages against bacterial spot. Balogh et al. (2018) compared laboratory behavior, leaf persistence, and plant disease. Laboratory multiplication did not reliably predict disease control. Leaf persistence showed only a weak relationship with control. This finding challenges simple rankings based on one laboratory measurement.

4.3 Rice bacterial blight in a pot experiment

Jain et al. (2023) investigated a phage against bacterial blight of rice. Their plant experiment compared infected controls with two phage preparations. The researchers measured lesions at several times after infection. Figure 3 identifies the original published photograph and graph.

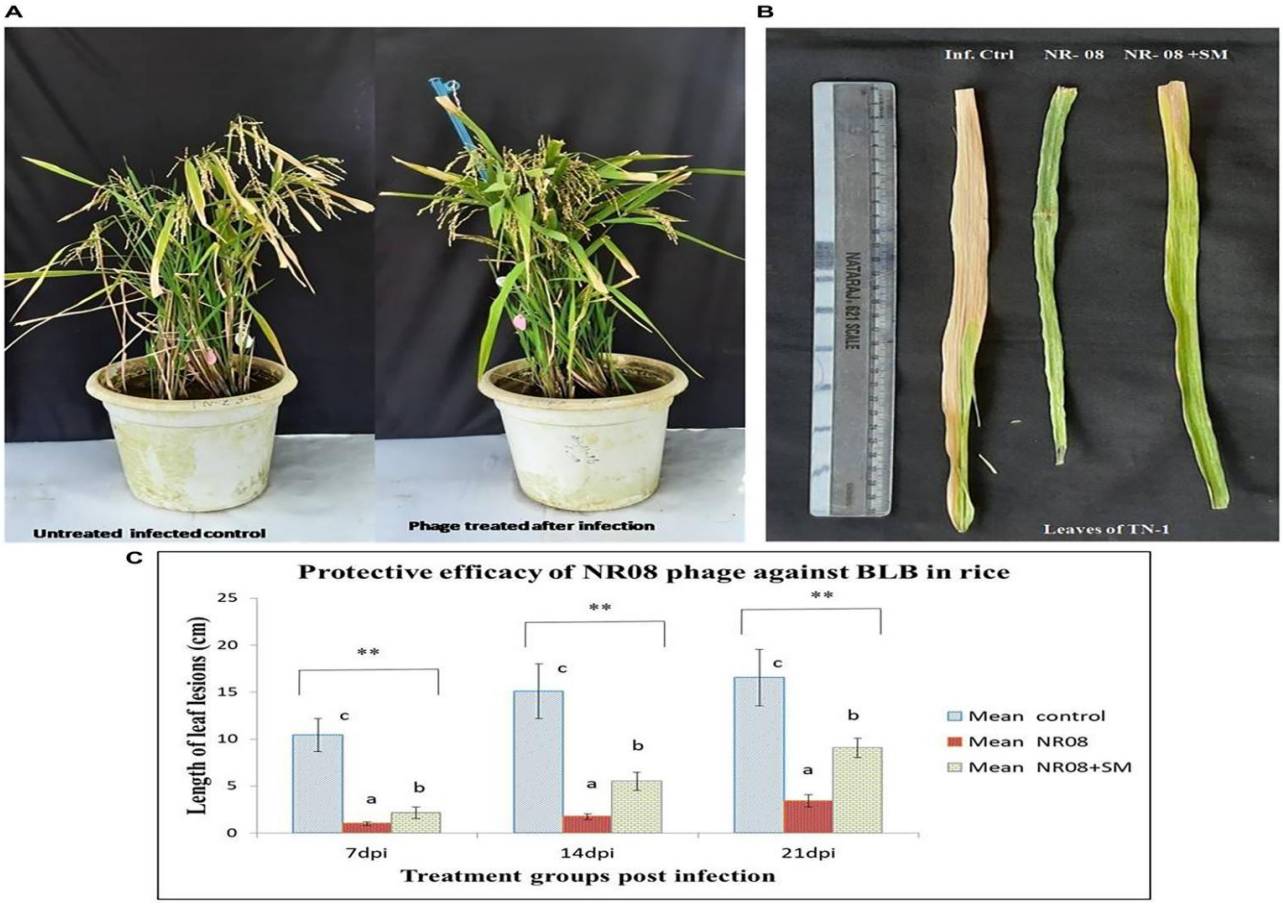


Figure 3 rice plant photographs and lesion graph. Source: Jain et al. (2023).

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The reported untreated leaves had a mean lesion length of 16.55 cm at day 21. Leaves treated with the unamended phage had a mean lesion length of 3.43 cm. The corresponding reported disease reduction was 79.27%. These values describe one pot experiment, not expected field performance everywhere (Jain et al., 2023).

The same authors tested a preparation containing a milk additive. Its mean lesion length at day 21 was 9.08 cm. That value was lower than the untreated control but higher than the unamended phage treatment. Table 2 presents the reported means and standard deviations. Figure 4 displays the same means with their reported variation.

Table 2 Rice lesion lengths reported by Jain et al. (2023)

Treatment	Day 7	Day 14	Day 21
Infected control	10.45 ± 1.77	15.10 ± 2.91	16.55 ± 3.02
Phage	1.02 ± 0.20	1.74 ± 0.32	3.43 ± 0.63
Phage with additive	2.15 ± 0.62	5.53 ± 0.96	9.08 ± 0.99

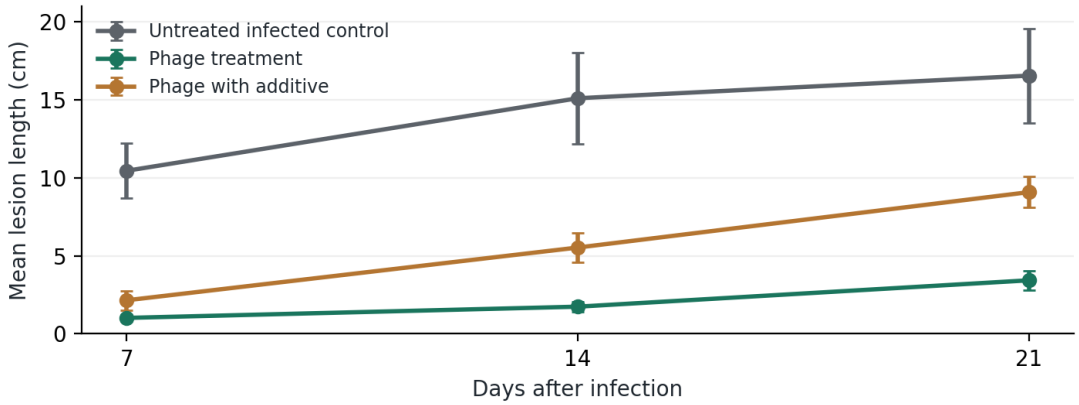


Figure 4 Rice lesion lengths from the pot experiment. Points show published means; bars show standard deviations. Source: Jain et al. (2023).

This comparison matters because a useful additive in one system may disappoint elsewhere. The rice study did not establish why the two preparations differed. It also did not prove that the additive always reduces phage performance. Crop conditions, phage properties, and evaluation methods may all matter. Further field work would be needed to assess practical consistency.

4.4 Persistence and bacterial response in a cherry orchard

Papp-Rupar et al. (2025) examined phages targeting *Pseudomonas syringae* in cherry. Their work included detached leaves and an orchard experiment. The orchard study tracked phages and bacteria on leaves and shoots. It also examined bacterial sensitivity and the leaf microbial community.

The phage mixture remained detectable at day 30 when the bacterial host was present. Without the added host, phages were detected early but not at day 30. Figure 5 summarizes selected reported observations. It does not estimate population size between sampling dates.

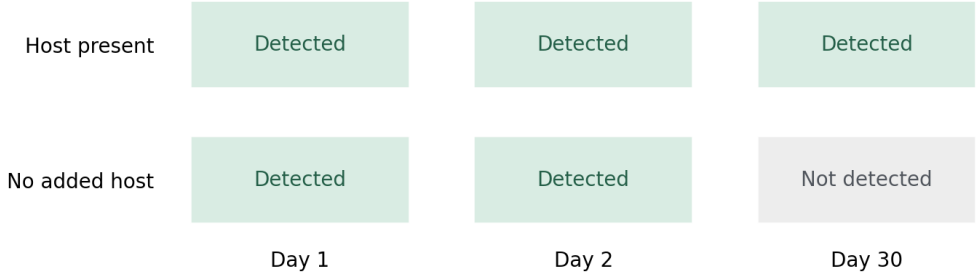


Figure 5 Selected phage detection results in the cherry orchard. These boxes show reported detection, not quantities. Source: Papp-Rupar et al. (2025)

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The same experiment reported an early reduction in bacterial numbers. However, this reduction did not continue throughout the 30-day observation period. Bacterial numbers later increased despite detectable phages. Persistence and disease protection should therefore not be treated as interchangeable outcomes (Papp-Rupar et al., 2025).

The authors did not detect resistance in the sampled bacterial population. They also reported no detectable effect on the measured cherry leaf microbiome. These findings apply to the tested mixture, samples, and orchard conditions. They do not rule out rare resistant bacteria or effects in other environments.

4.5 Fire blight control across orchard locations

Gdanetz et al. (2024) evaluated phages against apple blossom blight. Their field work covered several locations and growing seasons. Across the full set of tests, reported disease control ranged from 0% to 82.7%. This wide range shows that performance was not constant.

The authors reported stronger reductions in the New York tests of one commercial preparation. Those reductions ranged from 68.5% to 82.7% compared with untreated controls. At one Michigan location, reported reductions were 10% and 20% in two later tests. Figure 6 presents these selected ranges. They are not a formal statistical comparison between locations.

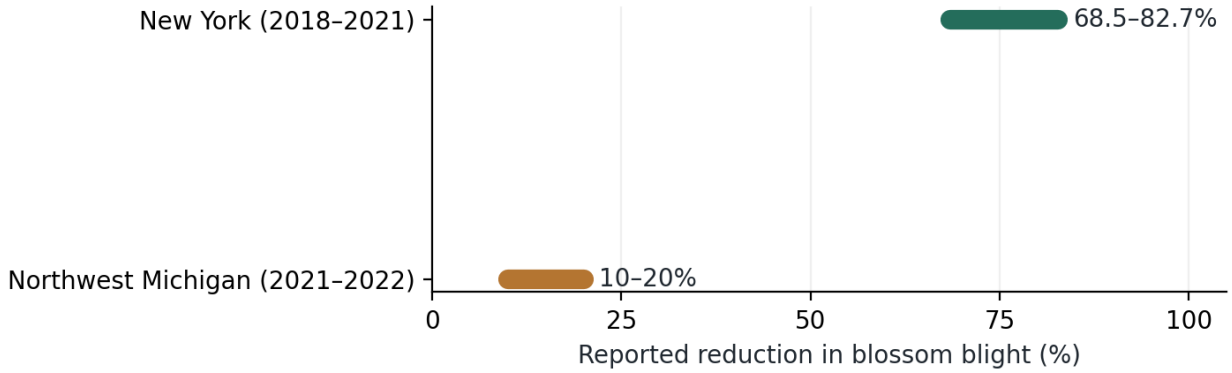


Figure 6 Selected ranges for one phage product in apple trials. Values summarize separate tests and years, not confidence intervals. Source: Gdanetz et al. (2024).

The authors also examined ultraviolet protectants. Added protection significantly improved disease control in only two of twelve tests. This result differs from the favorable persistence findings in some tomato studies. Better survival did not guarantee better field control elsewhere (Gdanetz et al., 2024; Iriarte et al., 2007).

Apple flower community diversity did not show a detected overall change over time. Some target groups declined temporarily after phage application. The study provides useful evidence for that setting. It cannot establish that every product leaves every plant-associated community unchanged (Gdanetz et al., 2024).

4.6 Fire blight experiments on detached fruit

Biosca et al. (2024) evaluated phages against the fire blight bacterium. Their experiments included immature fruit rather than full orchard disease cycles. Some treatments delayed symptoms and reduced severity under the tested conditions. Results differed among phage combinations and comparisons.

Detached fruit can provide a useful early test of plant protection. Its conditions still differ from a flowering orchard. Fruit tissues, bacterial contact, weather, and natural communities are not identical. An effective fruit result therefore needs field confirmation.

4.7 Existing sensitivity variation in fire blight bacteria

Schnabel and Jones (2001) examined five phages and 52 bacterial strains. Twenty-two strains were sensitive to all five phages. Twenty-three strains were resistant to more than one phage. The remaining seven resisted exactly one phage, based on the reported counts.

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Figure 7 displays these three categories. The data show existing differences among the tested strains. They do not show that field treatment caused those differences. This distinction matters when monitoring begins after a product is already in use.

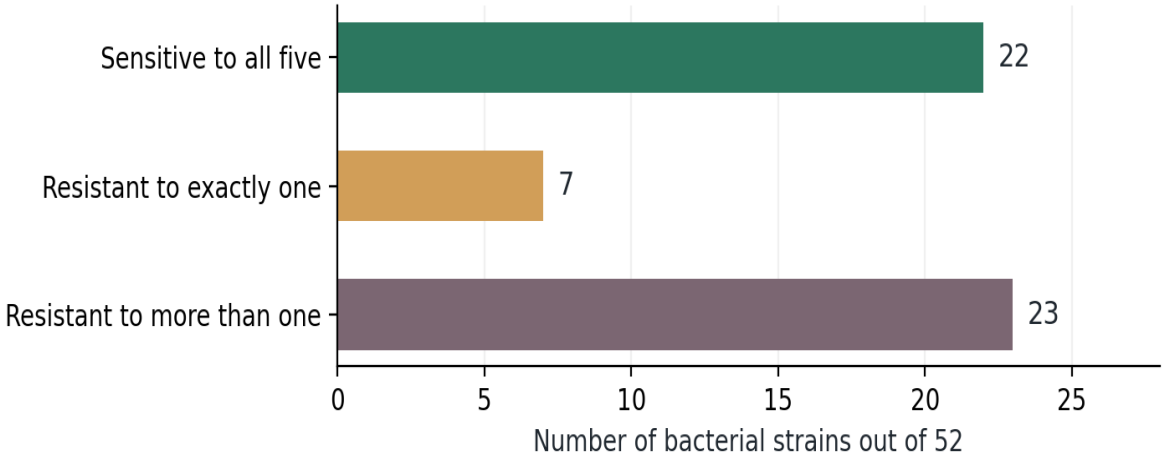


Figure 7 Sensitivity categories among 52 fire blight bacterial strains. Seven is calculated as 52 minus 22 minus 23. Source: Schnabel and Jones (2001).

The study also shows why a phage mixture may have uneven coverage. The number of phages alone does not describe their combined activity. Different bacterial collections can produce different sensitivity patterns. Any conclusion must specify the tested strains and phages (Schnabel & Jones, 2001).

4.8 Cross-resistance and differences among environments

Knecht et al. (2022) studied phage resistance in a fire blight bacterium. They observed temporary resistance in some experimental comparisons. They also found a stable resistant form associated with reduced sensitivity to other phages. The result demonstrates that resistance to one phage can affect more than one mixture component.

Different tests did not always give identical results for each phage. The authors therefore interpreted cross-resistance with the measurement context in mind. Their work was performed in laboratory conditions. It does not establish how often the same pattern occurs in orchards.

Hernandez and Koskella (2019) compared resistance in cultures and tomato leaves. Resistance arose readily in laboratory cultures during their experiments. The authors found little evidence of new phage-selected resistance inside leaves.

The result does not mean resistance is impossible in plants. It shows that the plant environment can alter the benefit of resistance. In the same study, phage effects on bacterial numbers differed by setting. Laboratory and plant observations should therefore be read together (Hernandez & Koskella, 2019).

5 Monitoring and Interpretation

5.1 Four linked outcomes

A useful assessment considers four questions together. Is active phage detectable? Are the bacteria present? Do sampled bacteria remain sensitive? Has plant disease changed? Each answer supplies a different part of the evidence.

Phage detection describes activity in the material examined. It does not establish complete coverage of a plant or field. Bacterial sensitivity describes responses under the assessment conditions. Disease scoring describes the plant outcome, which also depends on infection history and weather. Table 3 shows how these observations can be interpreted together.

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Table 3 How combined outcomes can guide interpretation

Observed pattern	Possible interpretation	Main limitation
Low active phage; disease persists	Exposure or limited contact may be involved.	This alone does not prove resistance.
Active phage; bacteria increase	Some bacteria may escape suppression.	Persistence alone does not show why.
Reduced sensitivity after treatment	A change in bacterial response is possible.	Existing strain differences need consideration.
Low disease; active phage detected	Treatment may be contributing to control.	Other influences require a comparison.

Comparisons become stronger when untreated observations are available. They also improve when the same outcome is followed over time. Disease may be patchy, and a few observations can miss local variation. The sampling design and detection limits should accompany every conclusion. These principles arise from differences among the published studies.

5.2 Reading low phage activity

Low phage activity may reflect environmental damage or limited host availability. Uneven distribution and measurement limits are additional possibilities. A low result alone cannot distinguish among these explanations. Weather records, plant tissue, and bacterial observations help place the result in context.

A decline may matter less after the period of greatest disease risk has passed. It may matter more when susceptible tissue remains exposed. This relationship depends on the disease and growing stage. The orchard and tomato studies illustrate why location and timing influence interpretation (Iriarte et al., 2007; Papp-Rupar et al., 2025).

5.3 Reading reduced bacterial sensitivity

Reduced sensitivity after treatment can signal a changing bacterial population. However, the same pattern can arise from differences in strains present before treatment. It can also reflect temporary responses or measurement variation. Baseline information makes these explanations easier to separate.

The term resistant should identify the phage and bacterial population involved. It should not imply resistance to all phages. A mixture may still affect bacteria that resist one component. Conversely, cross-resistance can reduce the value of several components (Knecht et al., 2022).

A finding of no detected resistance also needs careful wording. It means resistance was not observed in the tested samples. It does not prove that every bacterium remained sensitive. Small samples, limited locations, and short observations reduce certainty. This distinction applies to the cherry orchard findings (Papp-Rupar et al., 2025).

5.4 Disease outcomes and other explanations

Poor disease control does not prove that resistance caused failure. Phages may not persist, reach infected tissues, or match local strains. Disease may also be advanced before an effect becomes visible. Weather and differences in plant susceptibility can influence the result.

Likewise, visible improvement does not prove that bacteria were eliminated. A treated plant may retain bacterial populations while showing fewer symptoms. Disease measurements and bacterial measurements should remain separate. Balogh et al. (2018) found that several laboratory measures did not predict tomato disease control.

6 Discussion

6.1 Persistence is necessary to assess, but not sufficient

The reviewed studies show why persistence must be interpreted beside disease outcomes. Tomato leaf experiments found rapid losses under damaging environmental conditions. Cherry experiments found phage detection after an early bacterial reduction had faded. These examples address different crops and cannot be combined into one average.

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The rice study adds another caution. Its additive treatment was less effective than the unamended phage under tested conditions. Tomato studies had found benefits from some formulations. These findings are not contradictory because their hosts, phages, and measurements differed. They show why a formulation needs evidence in its intended system (Balogh et al., 2003; Jain et al., 2023).

Persistence also depends on where measurements are taken. Root, leaf, stem, and flower surfaces differ. Detection in one tissue cannot establish adequate activity elsewhere. Iriarte et al. (2012) found different levels across tomato tissues. That observation supports tissue-specific interpretation.

6.2 Resistance risk depends on context

Laboratory studies reveal possible resistance and cross-resistance. They can also identify differences among bacterial strains. Yet these findings do not establish the same frequency in a plant or field. Hernandez and Koskella (2019) observed a marked difference between laboratory and leaf environments.

The cherry orchard study did not detect resistance among its sampled bacteria. The earlier fire blight study found considerable variation in strain sensitivity. The two findings address different organisms and study designs. Neither can determine the outcome of every future phage treatment (Papp-Rupar et al., 2025; Schnabel & Jones, 2001).

Changes in resistance may carry costs for bacteria. Such costs can differ between a nutrient-rich setting and plant tissue. However, a cost should not be assumed without direct evidence. Some resistant bacteria may retain disease-causing ability. Monitoring should therefore avoid treating resistance as harmless by definition.

6.3 Mixtures and local bacterial diversity

A phage mixture can cover more bacterial strains than some individual phages. It can also reduce dependence on one phage response. However, these advantages are possible outcomes rather than guarantees. Components may overlap in their activity, and cross-resistance can occur (Knecht et al., 2022).

Local variation is especially relevant to crop disease management. A mixture studied against one bacterial collection may miss strains elsewhere. The apple study by Schnabel and Jones (2001) illustrates sensitivity differences. Field observations should be interpreted with their local bacterial populations in mind.

The Biosca et al. (2024) fruit experiments further show variation among mixtures. Some combinations reduced disease in specific comparisons. Other comparisons were less convincing. A mixture's name or number of components cannot replace measured performance.

6.4 What field trials add

Field trials include changing light, moisture, plant growth, and natural microbial communities. They can expose weaknesses hidden by controlled experiments. They also show whether disease reduction occurs under realistic production conditions. The apple trials revealed wide differences among locations and years (Gdanetz et al., 2024).

Field findings still have limits. A trial may cover only a few seasons or varieties. It may not represent every weather pattern or local pathogen population. A good result at one location should not be promised elsewhere. Multi-location repetition is more informative than a single favorable season.

Economic effects are also important. A measurable disease reduction may not always increase marketable yield. Additional evaluation should consider crop losses, product costs, and other management measures. The reviewed studies do not provide enough comparable economic evidence for a general estimate.

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6.5 Microbial community and environmental questions

Phages are often described as selective, but selectivity has limits. The actual host range depends on the phage and bacterial collection tested. A narrow laboratory result does not establish every environmental interaction. Field community measurements can provide additional evidence (Buttimer et al., 2017).

The cherry study did not detect a microbiome effect under its conditions. The apple study found no overall change in measured diversity over time. Some bacterial groups changed temporarily in the apple study. These results are encouraging but not universal guarantees (Gdanetz et al., 2024; Papp-Rupar et al., 2025).

Disease management should follow applicable product labels and local plant protection rules. Evidence from an experimental study does not itself authorize a commercial treatment. Regulations and registered uses differ among countries. Research decisions should also consider crop safety and the wider production system.

6.6 Research gaps

Longer studies are needed to follow bacterial sensitivity across growing seasons. This is particularly important where treatments are repeatedly used. Studies should report pre-treatment sensitivity when available. They should also distinguish stable resistance from temporary reductions in sensitivity.

Researchers need paired observations of active phage, bacteria, and disease. Studies that measure only one outcome leave competing explanations unresolved. Clear reporting of detection limits would improve interpretation. Comparable disease measures would also help readers compare studies.

More evidence is needed from commercial fields and diverse climates. Important crops in South Asia also require local evaluation. Rice and tomato studies provide useful starting points. Their findings cannot be transferred directly to every Pakistani production area.

Future economic studies should include marketable yield and treatment costs. Long-term community observations would also strengthen environmental assessment. Such work can help identify where phages make a useful contribution. It should report weak or failed results as clearly as successful ones.

7 Limitations

This review selected studies for relevance rather than through a formal systematic search. Some suitable studies may therefore have been missed. The evidence includes different crops, pathogens, and outcome measures. Direct comparisons remain limited.

Some reported experiments used controlled conditions or detached plant material. These conditions cannot fully reproduce commercial fields. Individual studies also differed in sample size and observation period. No pooled effect size was calculated.

The review reports published findings rather than independent verification of raw data. Some original figures may require readers to consult publisher pages. Percentages and photographs should be interpreted within each study's design. The document does not report newly conducted experiments.

8 Conclusion

Phages have reduced bacterial disease in several published plant experiments. Their performance varied across crops, locations, and study conditions. Active phage persistence and bacterial sensitivity are both relevant to the outcome. Neither measure alone guarantees disease control.

Tomato research showed that environmental exposure can reduce phage activity. Rice and apple experiments showed meaningful but variable disease reduction. Cherry work showed that detectable phage did not ensure lasting bacterial suppression. Resistance also differed between laboratory and plant settings.

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Reliable assessment needs disease outcomes alongside evidence on phages and bacteria. Reports should describe uncertainty, local conditions, and study limitations. Longer field studies can clarify how these relationships change over time. Until then, results should be applied only within the limits of their evidence.

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