Stallion Journal for Multidisciplinary Associated Research Studies
ISSN (Online): 2583-3340
Volume-1 Issue-2 || April 2022 || PP. 108-119 https://doi.org/10.55544/sjmars.1.2.14

Environmental and Application Factors Associated with *Bacillus*-Based Control of Soilborne Crop Diseases

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www.sjmars.com || Vol. 1 No. 2 (2022): April Issue

Date of Submission: 30-03-2022	**Date of Acceptance:** 25-04-2022	**Date of Publication:** 30-04-2022

ABSTRACT

Soilborne diseases damage crop roots and reduce harvests across many farming systems. Bacillus treatments can reduce these losses, although their performance changes between experiments and farms. This paper examines environmental and application factors using published experiments and publicly accessible research records. The evidence covers fungal, oomycete, and bacterial diseases affecting vegetables, beans, and sugar beet. Reported treatment means were extracted without inventing observations or combining incompatible disease scales. Temperature, soil water, acidity, organic inputs, root colonization, formulation, dose, and application timing were examined. Within individual studies, stronger protection often followed suitable root placement and supportive carrier materials. One cucumber experiment reported disease incidences of 75%, 50%, and 25% for control, 1%, and 2% fertilizer treatments. Another experiment increased control efficacy from 53.6% to 72.2% through combined application methods. However, Bacillus subtilis MBI 600 failed against Pythium despite persisting mainly as spores. Field evidence also showed that benefits depended on disease pressure, treatment schedules, and strain combinations. Several experiments linked protection with root biofilms, antimicrobial compounds, or changes in plant defense. These findings support matching each strain and formulation with its intended crop, pathogen, and soil conditions. They do not establish one temperature, acidity level, or dose suitable for every Bacillus product. Better trials should measure viable cells, root establishment, environmental conditions, disease development, and marketable yield together. Such measurements would make practical recommendations more reliable and easier to compare.

Keywords- *Bacillus*; biological control; soilborne diseases; root colonization; soil environment; application methods; bioorganic fertilizer.

I. INTRODUCTION

Soilborne diseases begin where crop roots meet soil organisms. Their effects include poor emergence, damaged roots, wilt, and reduced harvests. Disease control becomes difficult when pathogens survive between successive crops. Treatments must reach the infection zone while roots are still vulnerable. *Bacillus* has received attention because selected strains can establish near roots and produce protective compounds. However, evidence from one strain cannot represent every member of the genus.

The main problem concerns inconsistent protection under changing conditions. A treatment may work in a pot but give weaker results in a field. Root growth, pathogen pressure, soil conditions, and product delivery can change together. Their combined effects are difficult to identify through laboratory screening alone. The practical question therefore extends beyond whether a bacterium inhibits a pathogen. It asks when that activity produces useful crop protection.

Chen et al. (2013) screened 60 natural *Bacillus subtilis* isolates against tomato bacterial wilt. Six isolates provided more than 50% protection under greenhouse conditions. Their experiments linked protection with genes supporting biofilm formation and root colonization. Biofilms are attached bacterial groups surrounded by a shared protective material. These

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findings identify root establishment as a biological requirement worth measuring. They also show why selecting strains through plate inhibition alone can miss important traits.

Field experience provides a different view of treatment performance. Estevez de Jensen et al. (2002) studied bean root rot across three growing seasons. Their results changed with season, disease pressure, and microbial combinations. Under severe pressure in 1999, only one combined treatment significantly improved disease severity and yield. That treatment included *Bacillus subtilis* MBI600 and *Rhizobium tropici*. This result supports testing the complete treatment within the intended production system.

Environmental factors can affect the crop, pathogen, and protective bacterium simultaneously. Their effects may strengthen or weaken each other. Application factors determine how much viable material reaches the root zone and when it arrives. Product storage can alter that starting amount before field application begins. Carrier materials can also affect nutrition, water retention, and microbial growth. These overlapping influences require careful interpretation.

This paper examines those relationships through reported experiments. Its first aim is to identify environmental factors with direct experimental support. Its second aim is to compare delivery methods, doses, formulations, and treatment schedules. Its third aim is to separate measured effects from reasonable explanations. The central argument is that useful protection depends on matching biological activity with local conditions. Evidence strength depends on the experimental design supporting that match.

II. MATERIALS AND METHODS

2.1 Research design and source selection

This study used a structured narrative synthesis of primary research. Targeted searches were completed on October 28, 2021. Search phrases combined *Bacillus* with soilborne disease, temperature, moisture, acidity, dose, formulation, and application timing. Additional searches used crop names, strain codes, and disease names. Publisher websites, PubMed records, and institutional repositories were checked. References within relevant papers helped identify related experiments. The search was selective rather than exhaustive. No complete database export or registered review protocol was produced. Therefore, this paper does not claim systematic review coverage. It also does not estimate publication bias. Eighteen primary research sources supported the synthesis. One source was a doctoral dissertation available through its public repository abstract. Other sources were journal articles with public abstracts or full texts.

Studies were included when they reported a named *Bacillus* strain or a clearly described *Bacillus* treatment. They also required a crop disease endpoint or a directly relevant colonization experiment. Laboratory mechanism studies were retained when they explained root protection. Field experiments received greater practical weight than plate assays. However, field evidence was not treated as proof of every proposed mechanism.

Studies addressing only insect control or food preservation were excluded. Mayor Reports without identifiable source details were also excluded. Public availability referred to research records, published results, and accessible figures. It did not imply that individual plant observations were available. Repository abstracts supported only the information explicitly reported there.

Table 1. Experimental evidence used in the synthesis

Research setting	Representative sources	Main use
Field trials	Chou et al. (2022); Estevez de Jensen et al. (2002)	Crop protection under farm exposure
Controlled soil environment	Schmidt et al. (2004); Dal Soglio (1995)	Water, temperature, and acidity effects
Dose and delivery trials	Huang et al. (2017); Yang et al. (2014)	Rate and root placement comparisons
Mechanism experiments	Chen et al. (2013); Xu et al. (2013); Jia et al. (2015)	Biofilms and antimicrobial traits
Root and community studies	Liu et al. (2014); Kröber et al. (2014)	Recruitment and resident community responses

2.2 Information extracted

Extraction recorded the crop, pathogen, strain, experimental setting, treatment, comparator, endpoint, and assessment time. Environmental conditions were recorded when reported. These included temperature, soil water, acidity, and organic amendments. Application details included concentration, carrier, placement, frequency, and storage conditions. Missing details remained unreported rather than receiving assumed values.

Each numerical comparison stayed linked to its original source. Disease incidence, disease severity, growth, and yield were kept separate. A higher harvest was not automatically interpreted as stronger disease suppression. Such separation matters when organic carriers also supply nutrients.

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2.3 Data handling and descriptive calculations

Disease incidence means the percentage of assessed plants showing disease. Disease severity describes the extent of damage using a stated scale. A severity index combines individual scores into a normalized measure. These endpoints can answer different questions within the same experiment. They should not be exchanged without checking their definitions.

Relative disease reduction was calculated only within a study. The calculation used its own untreated or stated reference treatment. The equation was $R = 100 \times (C - T) / C$. Here, C represents the control value and T represents the treated value. The result describes relative reduction, provided C exceeds zero. It does not measure the percentage of plants cured.

Absolute change was calculated as $C - T$. For percentage endpoints, this difference was expressed in percentage points. Treatment efficacy differences were also expressed in percentage points. A reported change from 53.6% to 72.2% therefore equals 18.6 percentage points. This calculation adds no new experimental observation. It simply clarifies the size of an existing comparison.

Time-dependent disease burden was retained as the area under the disease progress curve, abbreviated AUDPC. This measure combines disease intensity with assessment time. Its units depend on the original disease scale and time unit. Values from different scales were not pooled. Within-study comparisons remained useful when assessment schedules matched.

Table 2. Measurements and their interpretation

Measurement	Meaning	Comparison rule
Disease incidence	Plants showing disease, expressed as a percentage	Use the same disease definition and assessment date
Severity or severity index	Damage scored using the source scale	Preserve the scale and normalization method
Relative reduction	100 × (control − treatment) / control	Calculate within the same experiment
Absolute change	Control minus treatment	Use percentage points for percentage endpoints
AUDPC	Disease intensity integrated through time	Keep the disease scale and observation schedule consistent

2.4 Evidence interpretation and figure preparation

Randomized environmental treatments supported stronger causal claims than correlations. Mutation studies supported biological mechanisms when other traits were adequately considered. Amendment experiments were interpreted as complete treatment packages. They could not always separate bacterial effects from fertilizer effects.

No pooled effect, confidence interval, or new significance test was calculated. Studies differed in hosts, pathogens, disease scales, and exposure conditions. Complete replicate measurements were also unavailable for several comparisons. Charts therefore show reported summaries without invented error bars. Source figures remain available through publisher links. Captions identify the source, original location, and download link. Each numbered placeholder contains a chart that can be replaced during journal formatting.

III. RESULTS

3.1 Temperature and the difference between survival and protection

Temperature did not affect every biological process in the same way. Schmidt et al. (2004) tested sugar beet treatments across temperatures ranging from 7°C to 35°C. They also varied soil matric potential. This term describes how strongly soil holds water. *Bacillus subtilis* MBI 600 populations consisted largely of spores. Their abundance was unaffected by temperature and decreased slightly under drier conditions. Yet the treatment produced no significant protection against *Pythium ultimum*.

That result separates persistence from useful activity. Detecting spores does not demonstrate enough growth or protective compound production near roots. It also does not establish that the strain targets the tested pathogen effectively. This distinction is especially relevant when product quality is judged through viable counts alone. A count can describe survival while leaving disease control unresolved.

The same experiment included *Pseudomonas fluorescens* B5. Its temperature responses must not be assigned to *Bacillus*. Differences between the bacteria show why a shared trial still requires strain-specific interpretation. General statements about bacterial temperature preferences can hide these differences.

Temperature also affects materials produced before application. Li et al. (2024) tested *Bacillus velezensis* Bv-116 fermentation supernatant under heat, acidity, and ultraviolet exposure. Figure 1 presents those laboratory stability tests. These tests measured retained inhibitory activity after treatment. They did not measure live bacterial performance in heated agricultural soil.

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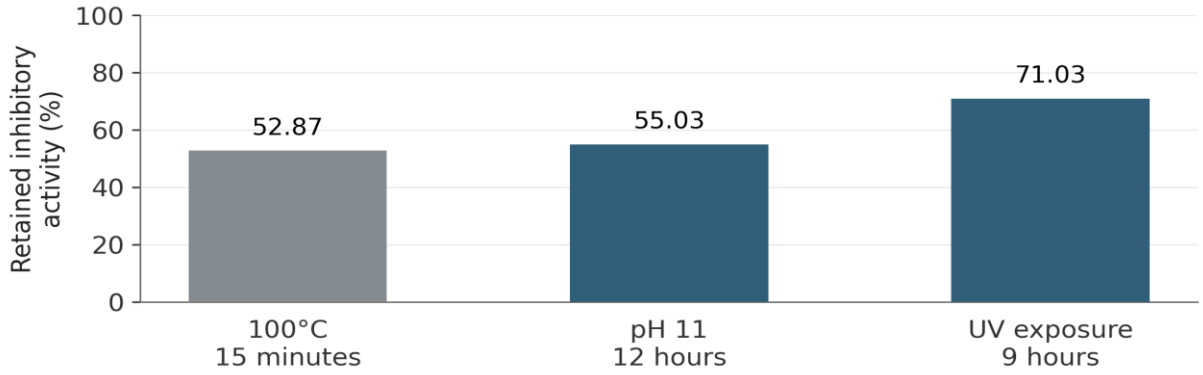


Figure 1 Retained inhibitory activity after separate laboratory stress treatments. Source: Li et al. (2024).

The distinction changes practical interpretation. A stable extracellular compound may remain active after bacterial growth stops. Conversely, surviving spores may require favorable root conditions before protection develops. Product assessment should therefore distinguish live cells, spores, and cell-free materials. Their temperature responses answer related but separate questions. These findings support measuring the protective function expected from each formulation.

3.2 Soil water and acidity

The sugar beet experiment used matric potentials of −7, −140, and −330 kPa for colonization assessments. At −330 kPa, water shortage limited emergence independently of *Pythium* infection (Schmidt et al., 2004). This finding matters when disease control is inferred from seedling survival. Poor emergence may reflect drought, infection, or both. A useful experiment needs uninfected controls under the same water conditions.

No universal irrigation target follows from these values. The relationship between water content and matric potential changes with soil texture. A given percentage of water can represent different stresses in different soils. Practical comparisons should therefore report the measurement method and soil characteristics. Describing a pot as adequately watered gives limited information about root exposure.

Acidity requires similar care. Dal Soglio (1995) examined soybean *Rhizoctonia* disease using *Bacillus megaterium* and *Trichoderma harzianum*. The public dissertation abstract reports experiments at soil pH 5.5 and 7.0. Disease was more severe at pH 7.0. Combined antagonists showed synergy at pH 5.5, but not at pH 7.0. This evidence came from a specific mixed biological system. The full dissertation was restricted, so no additional details were inferred.

Table 3. Environmental evidence and its limits. Sources: Schmidt et al. (2004), Dal Soglio (1995), and Li et al. (2024).

Factor	Tested comparison	Supported interpretation
Temperature	7–35°C in sugar beet trials	MBI 600 survival did not establish Pythium control
Soil water	−7, −140, and −330 kPa for colonization	Dryness could limit emergence independently of infection
Soil acidity	pH 5.5 versus 7.0 in soybean	Mixed antagonist effects depended on the tested soil pH
Product stability	Heat, acidity, and UV exposure of supernatant	Retained inhibition described compound stability

Those findings cannot justify acidifying every crop soil. Crop nutrition and pathogen behavior also respond to acidity. A favorable value for one treatment may create problems in another production system. The evidence supports testing acidity as an interacting factor. It does not establish one preferred value for the genus.

Laboratory stability tests provide a different form of evidence. In Figure 1, the tested supernatant was readjusted before inhibitory activity was assessed. Its response therefore describes compound stability after exposure. It does not establish bacterial growth at the exposure pH. Confusing these endpoints would overstate environmental tolerance.

The combined interpretation is cautious but useful. Soil water and acidity should be measured around the roots during treatment evaluation. They should also be recorded before disease differences become large. Otherwise, later measurements may reflect disease damage rather than its original causes.

3.3 Organic materials and signals released by roots

Carrier materials can change the environment receiving a *Bacillus* inoculant. Their effects can include physical protection, additional nutrients, and altered microbial activity. These possibilities should be treated as separate explanations until experiments distinguish them. A treatment containing bacteria and compost is a combined intervention. Its outcome cannot automatically be assigned to the bacteria alone.

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Chen et al. (2023) loaded *Bacillus subtilis* SL-44 onto biochar and tested the formulation in radish pots. The authors reported a 59.88% decrease in *Fusarium* wilt incidence. They also reported improved soil properties and plant growth. The comparison supports examining biochar as part of the application package. It does not establish the same benefit for every biochar source, production temperature, or application rate.

Roots also alter the conditions experienced by applied bacteria. Liu et al. (2014) studied cucumber roots infected by *Fusarium oxysporum*. Infection increased colonization by *Bacillus amyloliquefaciens* SQR9 by 3.30-fold compared with controls. Citric acid acted as a chemical attractant. Fumaric acid stimulated biofilm formation. These experiments identified distinct roles for individual root compounds.

The result does not mean that infection improves crop health. It shows that an infected plant can change bacterial recruitment. Recruitment is only one step toward protection. The timing of recruitment may still be too late for heavily damaged roots. This interpretation supports preventive placement while avoiding claims that all root infection recruits useful bacteria.

The physical and chemical setting therefore has two origins. Soil and carrier materials establish part of the environment. Living roots change that environment through growth and released compounds. Testing bacteria in rich laboratory broth captures only part of this relationship. A root-associated assay can reveal whether the strain reaches and remains near the intended site.

Application studies should consequently distinguish bulk soil from soil attached to roots. Bulk measurements may miss a useful population concentrated near a small root region. Root measurements also need a clear denominator. Counts per gram of fresh root cannot be directly compared with counts per gram of dry root. Consistent sampling improves interpretation before more complicated explanations are attempted.

These findings support a practical sequence. First, confirm that the formulation reaches roots. Next, determine whether the strain remains active there. Finally, connect that activity with disease and harvest outcomes. Each step requires its own observation.

3.4 Dose responses in cucumber soil

Huang et al. (2017) compared four bioorganic fertilizer concentrations in cucumber pots. The concentrations were 0.25%, 0.5%, 1%, and 2% of soil mass. The product contained the strain SQR9 within an organic fertilizer. Source naming varied between *Bacillus amyloliquefaciens* and *Bacillus subtilis*. The strain code is therefore retained without treating these names as separate organisms.

Reported disease incidence was 75% in the reference treatment. Incidence reached 62.5%, 87.5%, 50%, and 25% across increasing fertilizer rates. Thus, the lower doses did not produce a consistent protective pattern. The highest two rates showed stronger suppression. Figure 2 displays the reported mean incidences. Uncertainty bars and comparison letters remain available in the source figure.

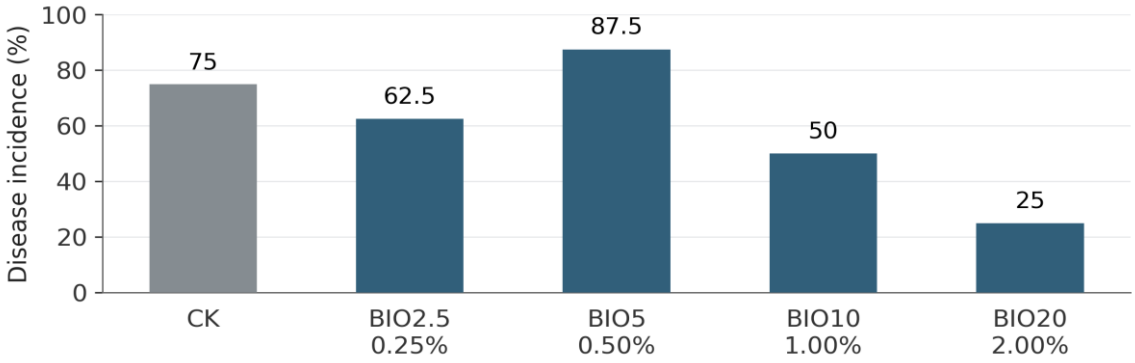


Figure 2 Bioorganic fertilizer rate and cucumber Fusarium wilt incidence. Source: Huang et al. (2017).

Table 4. Cucumber disease incidence and calculated relative reduction. Source: Huang et al. (2017)

Treatment	Fertilizer in soil	Incidence (%)	Reduction (%)
CK	Chemical reference	75.0	0.0
BIO2.5	0.25%	62.5	16.7
BIO5	0.50%	87.5	−16.7
BIO10	1.00%	50.0	33.3
BIO20	2.00%	25.0	66.7

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The calculations clarify the dose pattern within this experiment. They do not establish a universal *Bacillus* dose response. Fertilizer quantity and bacterial input changed together. Additional nutrients and organic material could therefore contribute to the outcome. The experiment also used pots containing five kilograms of soil. Direct conversion into a field rate would require incorporation depth, soil density, and treated soil volume.

A practical recommendation should preserve that distinction. Increasing a commercial product rate may increase cost without reproducing the pot environment. Local tests should compare viable bacterial input alongside carrier quantity. A carrier-only treatment would help identify how much protection depends on living bacteria. Nutrient-matched controls would further improve that comparison.

3.5 Root placement and repeated delivery

Yang et al. (2014) compared application approaches against cucumber *Fusarium* wilt. Adding *Bacillus subtilis* B006 powder to nursery substrate gave 53.6% control efficacy. Combining nursery treatment, transplant drenching, and organic fertilizer placement gave 72.2%. Organic fertilizer alone gave 29.4%. The combined approach also improved rhizosphere establishment and delayed disease development. Figure 3 summarizes the reported control values.

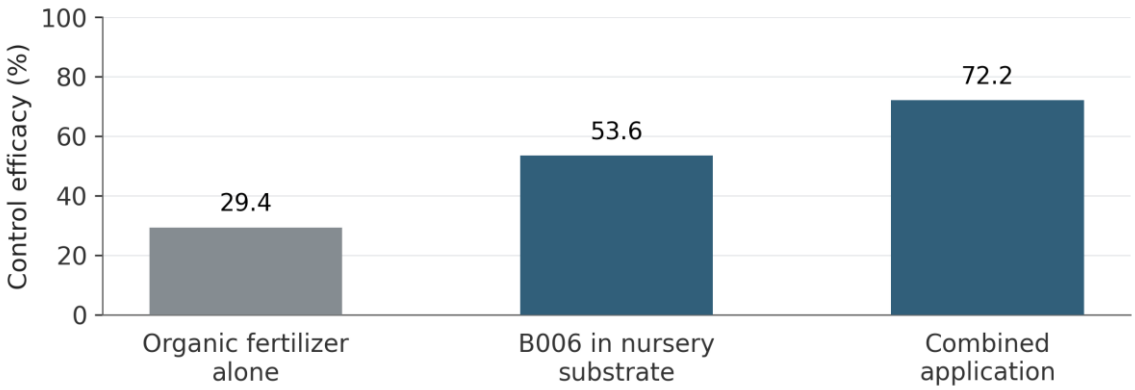


Figure 3 Application package and reported B006 control efficacy. Source: Yang et al. (2014).

The improvement from substrate treatment to combined delivery equals 18.6 percentage points. However, the comparison changed several treatment features together. It cannot show whether drenching, extra bacterial input, fertilizer placement, or their interaction caused the improvement. The result supports the combined package under its tested conditions. A separate factorial experiment would be needed to identify each contribution.

Placement remains biologically plausible because new roots create new infection sites. A one-time nursery treatment may not expose later root growth to the same bacterial population. Additional delivery could increase contact with the expanding root system. This explanation is an interpretation of the treatment pattern. It was not isolated experimentally by the reported comparison.

Timing also determines which stage of disease the treatment can influence. Protection before root infection differs from treatment after vascular damage develops. Future comparisons should state whether applications begin before inoculation, at transplanting, or after symptoms appear. They should also record the bacterial amount delivered at every application. Without these details, a repeated schedule can be mistaken for a timing effect alone.

Research on delivery should compare equal total inputs whenever possible. Dividing one total dose across several dates would test scheduling more clearly. Applying different total doses at different dates tests a broader management package. Both designs can be useful, but their conclusions differ.

These results support root-directed treatment as a promising application principle. They also show why treatment names need complete descriptions. A label such as soil application can hide important differences in placement depth, water volume, and root contact. Reporting these details helps another researcher repeat the work.

3.6 Strain traits and antimicrobial production

Strain traits changed disease control even within closely related bacteria. Jia et al. (2015) compared B006 with two surfactin-related mutants in cucumber soil. B006 achieved 42.9% disease suppression five weeks after transplanting. The overproducing mutant B841 achieved 22.6%, while deficient mutant B1020 achieved 7.1%. Figure 4 presents these reported outcomes. More surfactin production in laboratory broth therefore did not guarantee stronger plant protection.

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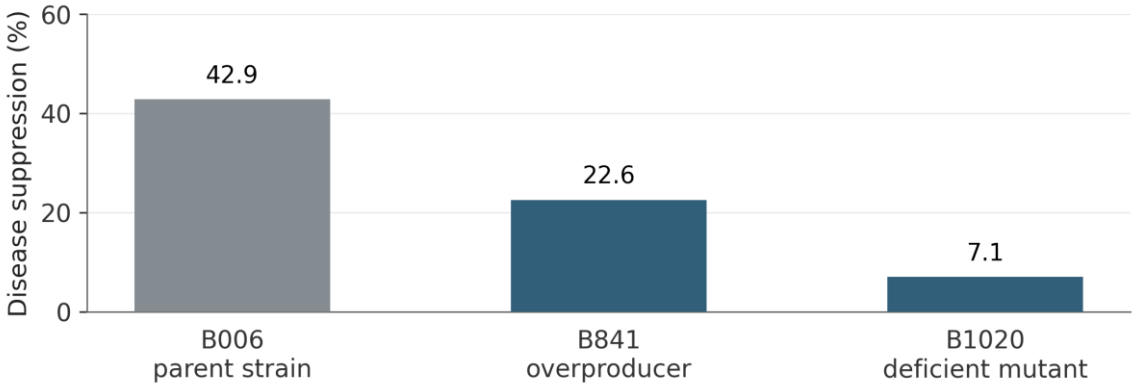


Figure 4 Disease suppression by B006 and surfactin-related mutants. Source: Jia et al. (2015).

The comparison cautions against using one laboratory trait as a complete selection rule. Mutations may affect colonization or other compounds alongside the targeted trait. An apparently improved laboratory phenotype can therefore perform poorly around living roots. Root competence should be evaluated together with compound production.

Xu et al. (2013) provided related evidence using SQR9 mutants. Disrupting bacillomycin D production greatly weakened antagonism against *Fusarium oxysporum*. Disrupting fengycin production did not cause the same loss in that experiment. Bacillomycin D also contributed to biofilm formation. These results show that antimicrobial activity and root establishment can share biological controls. Their effects cannot always be treated as independent processes.

Evidence from lettuce connected protective compounds with plant responses. Chowdhury et al. (2015) detected surfactin, fengycin, and bacillomycin D in the FZB42-treated rhizosphere. The wild strain enhanced a plant defense marker following pathogen challenge. Mutants lacking relevant products failed to provide equivalent protection. This supports a role for bacterial products under root-associated conditions. It does not establish equal importance for every compound in every host.

These findings explain why strain identity belongs in every treatment description. A species name alone can hide important differences in activity. The formulation also needs a traceable strain code. Otherwise, two products described as *Bacillus subtilis* may represent biologically different treatments. Reliable comparisons begin with that basic distinction.

3.7 Formulation quality and protection over time

Formulation quality affects the starting material delivered to crops. Chou et al. (2022) compared PMB01 in fermentation broth and wettable powder. After twelve months, reported population declines were 0.25 and 0.14 log units, respectively. Powder counts remained high after twenty-four months. This comparison supports measuring product viability under its actual storage conditions. It does not establish the shelf life of another strain or carrier.

Storage survival is only the first part of persistence. A viable product may still lose protective activity after application. Wu et al. (2016) studied *Bacillus amyloliquefaciens* SQY 162 in a tomato bioorganic fertilizer. Disease incidence was 65.18% lower than control after ten days. The reported reduction was 41.62% after twenty days. Figure 5 shows that the relative advantage changed with assessment time.

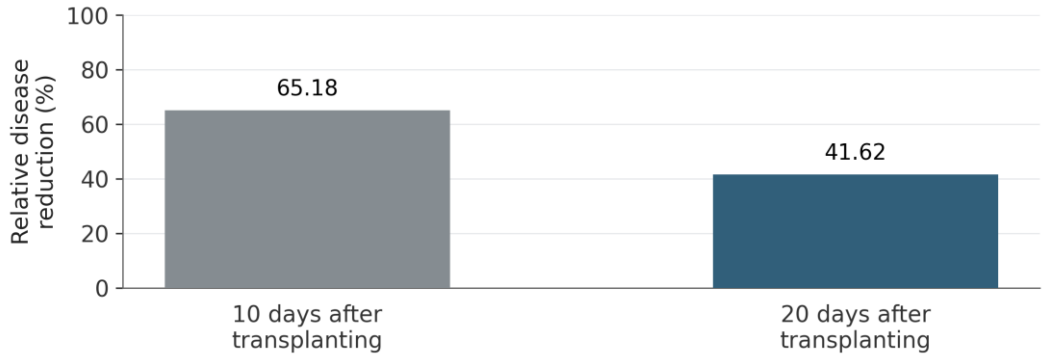


Figure 5 Relative reduction in tomato disease incidence across assessment dates. Source: Wu et al. (2016)

The difference between those reductions is 23.56 percentage points. This change does not directly measure bacterial death. Disease could have progressed differently between treatments while bacterial populations remained present. Host development or changing pathogen pressure could also contribute. Time-specific efficacy values need biological measurements before their causes can be assigned.

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A single final assessment can therefore hide useful information. Early protection may delay disease even when later differences become smaller. Alternatively, a treatment may establish slowly and provide stronger protection later. Repeated assessments help distinguish these patterns. They also support calculating disease progress using a consistent schedule.

Product evaluation should connect three kinds of measurements. Storage counts describe material entering the field. Root counts describe establishment after delivery. Disease measurements describe the resulting crop response. Measuring all three would help identify where a treatment loses performance. It would also distinguish a storage problem from poor root establishment.

This interpretation supports testing complete batches through their expected storage period. A fresh laboratory culture is an incomplete substitute for the product reaching growers. The tested material should resemble the formulation, age, and handling conditions expected during use.

3.8 Evidence from tomato field trials

Chou et al. (2022) tested PMB01 across ten tomato farms during 2014–2020. Treatments used three dilutions and five weekly root-zone drenches. Each application delivered 200 mL per plant. Farms used randomized blocks with four replicates per treatment. Figure 6 displays reported AUDPC ranges for the three illustrated trials. These illustrated trials were selected for strong control performance. Their ranges should not be presented as the full ten-farm distribution.

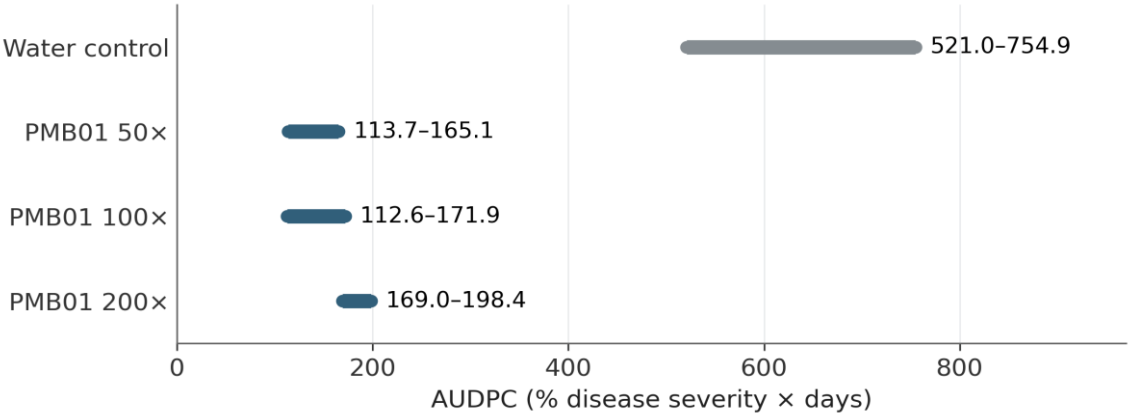


Figure 6 Reported tomato field disease-progress ranges with PMB01. Source: Chou et al. (2022).

These results provide useful field support for the tested treatment package. However, they do not separate the effects of formulation, application frequency, and initial disease pressure. A comparison with fewer applications would be required to judge schedule efficiency. Economic assessment would also need labor, product cost, and marketable harvest data.

Earlier field work also identified seasonal variation. Wei et al. (2011) tested organic fertilizer fortified with *Bacillus amyloliquefaciens* QL-5 and QL-18. Mixed inoculation reduced tomato bacterial wilt, but field efficacy depended on season. This finding supports local validation across more than one production period. It does not identify temperature as the only seasonal cause. Rainfall, crop growth, and pathogen exposure may also vary between seasons.

The bean experiments provide another caution. Estevez de Jensen et al. (2002) reported a 31% yield increase with GBO3 seed treatment in 1997. Under stronger disease pressure in 1999, only the MBI600–*Rhizobium* combination significantly improved disease and yield. This variation limits claims that a single successful season predicts later performance. It also supports testing compatibility with other established crop inputs.

Together, these experiments show that field benefits can be real and conditional. Useful validation should report unsuccessful comparisons alongside successful ones. Selecting only the best sites would overstate reliability. The practical target is repeatable benefit under the conditions where growers intend to apply the treatment.

3.9 Resident soil communities and root health

Soil organisms can respond to the crop, pathogen, and treatment simultaneously. Chowdhury et al. (2013) followed FZB42 in lettuce pot and field experiments. Treatment reduced average bottom-rot symptom categories from approximately five to three. Their community analysis showed stronger effects of sampling time and pathogen pressure than bacterial application. Figure 7 summarizes the reported symptom categories.

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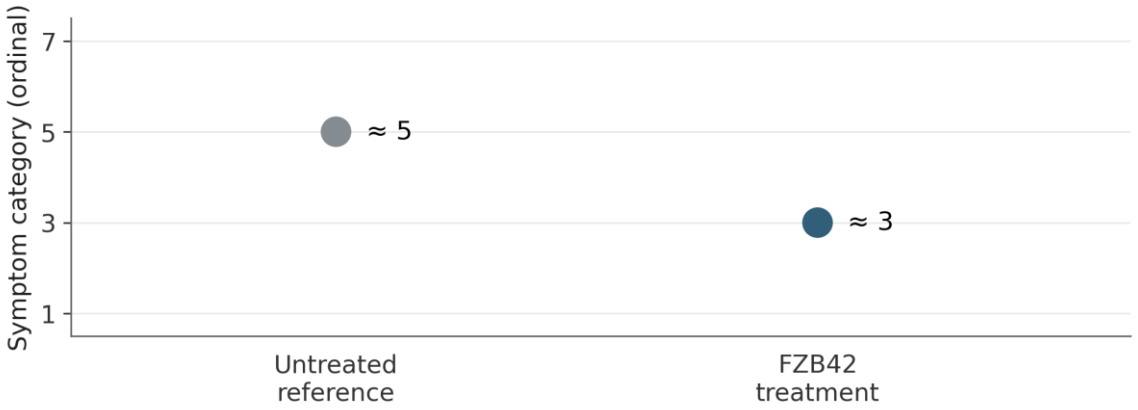


Figure 7 Approximate lettuce bottom-rot symptom categories reported in field research. Source: Chowdhury et al. (2013).

This result is useful because disease suppression occurred without a large measured community shift. It suggests that broad changes in community composition are not always required. Direct interactions or plant responses may contribute instead. The experiment does not establish that resident organisms were irrelevant. Its community method captured only part of soil microbial variation.

Kröber et al. (2014) used whole-community sequencing in a related FZB42 lettuce field study. They detected the applied strain across the observation period. Taxonomic and functional profiles differed only slightly between treated and untreated samples. Plant age produced clearer changes in community composition. This evidence supports considering crop development when interpreting microbial treatment effects.

The two studies should not be counted as fully independent confirmations of every FZB42 mechanism. They examined related research systems using different methods. Their agreement strengthens a focused interpretation about measured community change. It does not justify a general claim that every *Bacillus* application leaves soil communities unchanged.

A practical implication follows from this distinction. More microbial diversity is not automatically equivalent to better disease control. Community measurements need a clear relationship with plant health. Useful studies can combine composition, bacterial activity, pathogen abundance, and disease observations. Agreement across these measurements would provide a stronger explanation than composition alone.

3.10 Separating disease incidence from severity

Li et al. (2024) compared Bv-116 cells and its bioorganic fertilizer in cucumber pots. After twenty days, disease incidence reached 100% in pathogen-inoculated controls. Incidence was 57.78% with cells and 26.67% with bioorganic fertilizer. Corresponding severity indices were 68.44, 16.89, and 5.33. Figure 8 presents both endpoints without combining their scales.

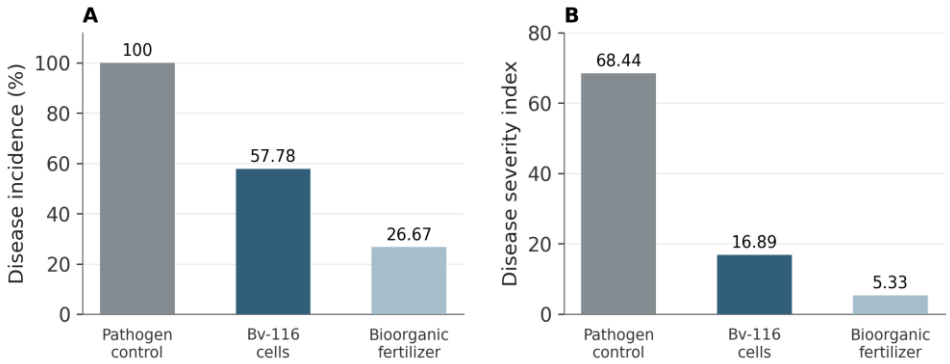


Figure 8 Cucumber disease incidence and severity after Bv-116 treatment.

These values describe different aspects of protection. The cell treatment left more than half the plants showing disease. Yet the average damage score was much lower than in controls. A treatment could therefore reduce damage substantially while leaving many plants classified as diseased. Reporting incidence alone would miss part of that response.

Calculations from rounded source values give severity reductions of approximately 75.32% and 92.21%. The paper reports control efficacies of 75.11% and 92.10%. These small differences may reflect unrounded data or averaging

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Stallion Journal for Multidisciplinary Associated Research Studies
ISSN (Online): 2583-3340
Volume-1 Issue-2 || April 2022 || PP. 108-119 https://doi.org/10.55544/sjmars.1.2.14

procedures. The published efficacies are retained when describing the authors' results. Rounded means are used only for the clearly labeled calculations here.

The fertilizer treatment combined bacteria with another material. Its stronger result therefore supports the complete formulation under the tested conditions. It does not identify a separate fertilizer effect without an appropriate matched comparison. Nor does this greenhouse result establish equivalent protection under open field exposure.

This example also shows why treatment success needs an agricultural endpoint. Lower symptom scores may improve growth, but marketable yield still requires measurement. The useful outcome depends on the crop and its harvest requirements. Trials should state that outcome before selecting their primary disease measurement.

IV. DISCUSSION

4.1 Environmental and application factors act together

The selected experiments support a connected explanation of *Bacillus* performance. Delivery determines the initial root exposure. Formulation affects whether viable material survives handling and reaches the crop. Root conditions then influence establishment and activity. Protection depends on whether that activity matches pathogen behavior and crop susceptibility. This explanation is a synthesis of the evidence rather than a separately tested model.

The strongest caution comes from the negative sugar beet result. *Bacillus* MBI 600 persisted but failed to provide significant *Pythium* protection (Schmidt et al., 2004). Persistence should therefore be treated as an intermediate measurement. The same reasoning applies to laboratory inhibition zones and compound concentrations. Each measurement describes a useful process, but none replaces a disease assessment.

Application packages often change several factors simultaneously. The B006 delivery study improved protection through a combined approach (Yang et al., 2014). However, its design did not isolate a timing effect from additional input or carrier effects. This limits causal interpretation while preserving the practical value of the package. Future work should decide whether its aim is explanation or management testing. Those aims require different comparisons.

Temperature and acidity provide similar examples of measurement choice. A controlled soil treatment can support an environmental effect within a defined system. A seasonal comparison can only associate performance with several changing conditions. A supernatant stability test addresses compounds after exposure. It cannot establish root colonization at the same temperature or acidity. Keeping these categories separate prevents stronger claims than the experiments support.

4.2 What the evidence can establish

The evidence supports strain-specific protection in several crop systems. It also supports root establishment as a recurring biological requirement. Genetic and root-associated experiments help connect biofilms and bacterial products with that protection. Chen et al. (2013), Xu et al. (2013), and Chowdhury et al. (2015) provide complementary examples. Their findings explain parts of the process without establishing one mechanism for all strains.

The evidence does not provide a universal environmental operating range. Crop species, pathogen identity, soil properties, and formulations differed too widely. Several studies also lacked complete environmental measurements. The available comparisons cannot rank moisture, acidity, temperature, and dose on one common scale. Their relative importance remains a local experimental question.

Practical interpretation should therefore begin with the intended use. Evidence from a matching crop, pathogen, and application package offers the strongest starting point. Evidence from another system can identify questions worth testing. It provides a weaker basis for adopting the same dose or schedule directly.

4.3 Implications for crop management and trial design

Growers need evidence about the product they can actually apply. A useful field comparison should therefore use the intended formulation and handling conditions. It should also include the usual crop management program. Disease pressure and treatment costs should be recorded throughout the crop cycle. These are proposed evaluation principles derived from the synthesis.

Compatibility deserves attention when *Bacillus* joins an existing control program. Kondoh et al. (2001) combined *Bacillus subtilis* RB14-C with flutolanil against tomato *Rhizoctonia* damping-off. The combined treatment used one-quarter of the fungicide amount with similar disease control. Bacterial growth and iturin production were maintained, although surfactin production declined. This result demonstrates compatibility for the tested combination. It does not support mixing every *Bacillus* strain with every fungicide.

Table 5. Measurements proposed for practical validation

Trial stage	Measurement	Question addressed
Before use	Strain identity, viable count, and storage age	What biological material reaches the trial?
At application	Delivered amount, root placement, and water volume	Do treatments create comparable exposure?
During growth	Root counts, temperature, soil water, and pH	Does the treatment establish under local conditions?

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Disease assessment	Incidence, severity, and assessment dates	Does protection persist through the crop cycle?
At harvest	Marketable yield, treatment cost, and labor	Does protection provide useful farm value?

The most informative comparisons separate biological input from carrier input. A carrier-only control tests whether the supporting material provides protection independently. A bacterial treatment without the carrier can test whether the carrier improves delivery. Nutrient-matched controls become useful when fertilizer effects are substantial. These comparisons should use the same crop, soil, and pathogen exposure.

The experimental unit also needs clear definition. Several plants within one pot share an environment. They should not automatically be counted as independent replicates. Field plots share similar problems when treatment is applied to the whole plot. Analysis should follow the level receiving the independently assigned treatment.

Repeated disease measurements can connect protection with harvest performance. A treatment that delays symptoms may still provide useful benefits. Another treatment may improve early growth without reducing later disease. Marketable yield helps distinguish these outcomes. Cost per treated area and labor per application would complete the practical comparison.

Local testing should produce a decision about a defined management package. It should identify the conditions under which benefits remain repeatable. That approach gives a clearer recommendation than selecting the highest reported suppression percentage from unrelated papers.

V. LIMITATIONS

This synthesis used targeted searches and selected primary sources. It was not a registered systematic review or a statistical meta-analysis. Relevant experiments may therefore have been missed. Positive studies may also be easier to locate than unsuccessful trials. No numerical estimate of that bias was possible.

Some reports supplied full methods and figures, while others supplied only accessible abstracts. The dissertation evidence about soil acidity came from a public repository abstract. Its restricted full text prevented further extraction. That evidence therefore supports only the stated comparison. It should receive less weight than a fully inspectable experiment.

Published summaries could not support reconstruction of individual observations. Redrawn graphs consequently omit unavailable uncertainty measurements. Study-level percentages were not treated as independent plant records. Different disease scales also prevented direct pooling. Comparing all reported percentages as equivalent outcomes would create misleading precision.

Several treatment packages combined bacteria with fertilizer or other materials. Their outcomes could reflect bacterial activity, nutrition, physical changes, or interactions. A change in community composition also did not prove a causal role in suppression. Follow-up experiments would need to isolate those processes. Current associations remain useful for choosing those experiments.

Older studies sometimes used names that differ from present strain classifications. The original strain codes and source names were retained. No new taxonomic identification was attempted. This paper also did not evaluate regulatory approval, commercial availability, or product safety. Those questions require separate evidence for a specific formulation and location.

VI. CONCLUSION

Bacillus-based control can reduce soilborne crop disease under suitable conditions. Its success depends on the particular strain, pathogen, crop, formulation, and application package. Environmental measurements help explain performance but do not replace direct disease assessment. Root survival alone cannot establish that protection will occur.

The selected experiments support careful attention to dose, root placement, formulation quality, and repeated assessment. They also show that larger inputs do not always produce stronger protection. Soil water, acidity, and temperature should be tested within the intended crop system. No single favorable range applies across the evidence examined here.

Future studies should connect product viability, root establishment, disease development, and marketable yield. They should preserve unsuccessful results and report environmental conditions clearly. Matched controls would separate bacterial effects from supporting materials. These improvements would make recommendations more useful for researchers and growers.

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