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Review

Utilizing Environmentally Friendly Techniques for the Sustainable Control of Plant Pathogens: A Review

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Abstract

Utilizing environmentally friendly techniques for pathogen control in agriculture is a sustainable and eco-friendly approach to managing crop diseases. These techniques leverage the natural environment and ecosystem dynamics to reduce pathogen pressure, minimize the use of chemical inputs, and promote long-term agricultural productivity. Key strategies include crop rotation, intercropping, and maintaining biodiversity, all of which disrupt pathogen life cycles and enhance soil health. Biological control, such as introducing natural antagonists like beneficial fungi or bacteria, suppresses pathogen populations while promoting plant resilience. Additionally, practices such as mulching, soil solarization, and water management optimize environmental conditions to limit the development and spread of pathogens. These techniques also contribute to integrated pest management by providing sustainable, cost-effective solutions that reduce chemical dependency and mitigate climate change and other environmental impacts. This review discusses the importance of utilizing environmentally friendly techniques, highlighting their advantages, practical challenges, and limitations in different agro-ecological settings, and their role in advancing sustainable agriculture.

Keywords: biological control; soil biodiversity; intercropping; crop rotation; soil solarization; mulching

1. Introduction

1.1. Importance of Plant Disease Management

Although plant disease management has always been important, it has become increasingly complex due to recent challenges related to climate change, the appearance of emerging pathogens, resistance to fungicides, the reduction of allowed registered pesticides, and the difficulties in developing new products for plant pathogen control [1,2].

Throughout history, plant disease management has evolved across four principal phases: (i) limited intervention in old agricultural fields; (ii) mechanical and agronomical suppression techniques (plowing, rotations); (iii) extensive use of pesticides; and (iv) integrated pest management (IPM) endeavoring to achieve ecological, economic, and social balance [3].

1.2. Overview of Environmental Techniques for Pathogen Control

Environmental techniques for pathogen control are crucial components of sustainable agriculture and environmental management, aiming to minimize the reliance on chemical pesticides while preserving ecosystem health. These techniques use a variety of strategies, from physical methods and biological control to cultural practices, to create unfavorable conditions for pathogens or improve host organism resilience (Figure 1). Each approach leverages natural principles to manage pathogens more effectively while reducing potential adverse impacts on soil, water, and non-target organisms.

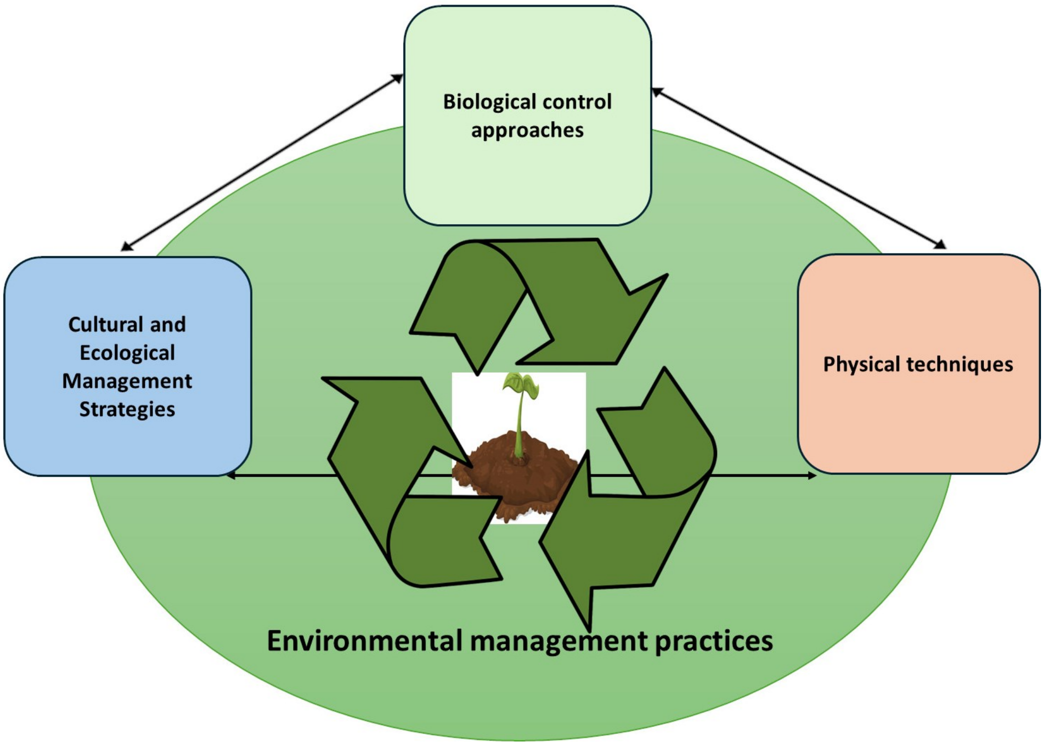

Figure 1. Environmental management practices used for the control of plant pathogens.

One key group of environmental pathogen control techniques involves physical methods, which manipulate environmental conditions to disrupt pathogen life cycles. For example, soil solarization is a widely used technique that relies on covering the soil with transparent plastic sheeting, allowing solar radiation to heat the soil to temperatures lethal to many soil-borne pathogens. This process can effectively reduce pathogen loads without the use of synthetic chemicals [4].

Similarly, controlled irrigation practices can limit excess moisture, which often promotes fungal and bacterial pathogens. Adjusting irrigation schedules or using drip irrigation helps reduce humidity and soil moisture, creating an environment less conducive to pathogen proliferation [5].

Biological control methods are another foundational component of environmental pathogen management, using natural antagonists to suppress harmful organisms. Beneficial microorganisms such as *Bacillus*, *Pseudomonas*, *Trichoderma*, and *Gliocladium* species (spp.) can act as biocontrol agents against a wide range of plant pathogens. These organisms use multiple mechanisms, including competition, parasitism, antibiosis, and the induction of plant defense responses, to limit pathogen growth and infection. Biological control has gained considerable attention because of its environmentally friendly nature and ability to establish long-term pathogen suppression [6].

Cultural practices play an essential role in the management of pathogens by altering the conditions that support the survival and infection of a pathogen [7,8]. Crop rotation, for instance, is a long-standing practice that helps break pathogen life cycles by rotating crops with non-host plants, reducing pathogen populations in the soil over time. Cover cropping, another cultural practice, improves soil structure and supports beneficial microorganisms that compete with or inhibit pathogens. Additionally, modifying planting dates and practicing proper sanitation can prevent pathogen spread and reduces inoculum sources for the following season.

Another approach gaining interest is represented by the use of organic soil amendments, such as compost, animal manure, and plant residues [9]. These amendments serve as carbon sources for microbes, improving soil health and fertility while enhancing its microbial community, which competes with or directly inhibits pathogens. Organic matter additions have also been found to increase populations of beneficial microbes that produce enzymes and antimicrobial compounds, adding another layer of defense against soil-borne pathogens. Additionally, organic amendments can increase soil water-holding capacity and nutrient availability, helping plants better resist pathogens. Research has shown that the addition of specific composts can suppress soil-borne pathogens like *Pythium* and *Fusarium* and increase plant health by enhancing the soil microbiome's diversity and resilience.

Genetic resistance through breeding is another environmentally sustainable method for pathogen control, through which resistant plant varieties are developed to naturally withstand certain pathogens. Breeding plants for disease resistance can significantly reduce disease incidence without relying on chemical inputs. However, pathogens can evolve and overcome these resistances, making it necessary to develop and rotate resistant crop varieties regularly.

IPM combines these techniques into a cohesive strategy, aiming for long-term pathogen control with a minimal environmental impact [10]. By using a combination of cultural practices, biological control, and physical barriers, IPM seeks to prevent pathogen establishment and spread while also monitoring pathogen populations to apply chemical interventions only as a last resort. IPM is especially valuable because it allows for flexible management strategies tailored to specific pathogen threats and environmental conditions, thereby optimizing pathogen control and reducing ecological impact.

In summary, environmentally friendly techniques for pathogen control leverage physical, biological, and cultural methods to limit pathogen proliferation while promoting a balanced ecosystem. These methods minimize the use of chemical inputs and contribute to sustainable agricultural practices. The continued innovation and integration of these approaches, along with advancements in plant breeding and microbial applications, hold promise for effective and environmentally responsible pathogen management.

1.3. Scope and Objectives of the Review

The review aims to provide a comprehensive analysis of non-chemical strategies for the sustainable and eco-friendly management of plant pathogens across agricultural and natural ecosystems. By examining physical techniques, biological control, soil health management, and integrated pest management, the study seeks to evaluate the effectiveness, benefits, and limitations of environmentally friendly techniques for controlling plant pathogens. While previous reviews have typically focused on individual environmental control methods or specific pathogen groups, this review uniquely synthesizes the synergistic interactions between multiple non-chemical approaches across diverse agricultural systems and environmental conditions. Unlike the existing literature, which often treats techniques in isolation, our comprehensive analysis systematically evaluates the combined effectiveness of environmentally friendly management strategies, providing novel insights into optimization pathways for sustainable pathogen control. This review distinctively addresses current knowledge gaps in understanding the mechanistic interactions between soil health, microbial communities, and pathogen suppression under varying climatic conditions, offering evidence-based recommendations for climate-resilient disease management. Ultimately, the study aims to serve as a valuable resource for researchers, agronomists, and policymakers by promoting sustainable pathogen management practices that minimize environmental impacts, support agricultural productivity, and reduce reliance on chemical pesticides.

2. Environmental Factors and Plant–Pathogen Interactions

2.1. Abiotic Factors

Pathogenic fungi, oomycetes, bacteria, phytoplasmas, viruses, and viroids present causal agents of plant diseases that provoke important qualitative and quantitative yield reductions. Notwithstanding the progress of science and technology, yield losses of crop production at a global level from various pests, reach about 30% of the total production today. The development of plant diseases caused by these pathogens is affected by different abiotic factors such as temperature, CO_2, light intensity, relative humidity, precipitation patterns, soil moisture, soil composition, and the pH of the growing medium [11–15]. Temperature is a key factor since it impacts pathogen activation and disease development. Soil pH may influence plant susceptibility to plant diseases and the activity of microbial communities in a changed pH environment [14,16]. Unbalanced nutrition and contaminants importantly influence pathogen development and plant resilience [15]. All of these abiotic factors collectively influence the interaction between the plant pathogen and its host, which significantly shapes the dynamics of plant disease through the temporal dimension.

2.2. Biotic Factors

Biotic factors, including microbial communities and biodiversity, play a vital role in controlling plant pathogens by naturally suppressing diseases and promoting plant health. Microbial communities inhibit pathogens through competition, antimicrobial compound production, and parasitism, while also priming plant immune responses. Biodiversity enhances ecosystem resilience, reducing pathogen spread through the “dilution effect” and ensuring functional redundancy. Specific bacteria, such as *Bacillus* spp. and *Pseudomonas* spp., are known to inhibit pathogens like *Fusarium* spp. through competition and parasitism [17,18]. Specific interactions, such as mycoparasitism by *Trichoderma* spp. or predation by soil organisms, further reduce pathogen populations. Symbiotic organisms like mycorrhizal fungi and nitrogen-fixing bacteria [19] improve plant stress tolerance and indirectly lower susceptibility to pathogens. Microbial communities can trigger systemic resistance in plants, enhancing their ability to fend off diseases [18]. Despite challenges like environmental variability and pathogen adaptation, these biotic interactions are increasingly harnessed in agriculture through biocontrol agents (BCAs), microbiome engineering, and conservation practices. Practices like crop rotation and minimal tillage preserve microbial diversity, reducing disease pressure by disrupting pathogen life cycles [20]. In addition, healthy soils with rich microbial communities are less conducive to disease, as seen in suppressive soils where pathogens are present but do not cause significant disease [17]. Biotic factors offer a sustainable and effective approach to plant pathogen control, highlighting the importance of maintaining biodiversity and leveraging microbial communities for improved plant health. While the benefits of enhancing soil microbial diversity are clear, challenges remain, such as the unpredictability of certain plant growth-promoting rhizobacteria (PGPR) and the potential risks associated with using organic amendments that may harbor antibiotic resistance genes [20].

2.3. Impact of Climate Change on Plant Disease Dynamics

More recently, climate change has also had an important impact on plant pathogens and their interactions with plant hosts. Thus, climate change, through alterations in environmental factors, significantly shapes the dynamics of plant diseases by affecting plant pathogens, plant hosts, and their interactions. Labouyrie et al. [21] showed that climate change based on warming and altered humidity enhanced the presence of certain functional microorganism groups, such as plant pathogens, but reduced the abundance of others, such as beneficial arbuscular mycorrhizal fungi. Climate change may further promote the appearance of new pathogenic strains and the spread of plant pathogens into new geographic areas [22–28]. Climate change, especially temperature fluctuations, influences the pathogenesis of phytopathogenic fungi, whose life stages are intricately and closely linked to temperature [29,30]. Increased temperatures influence the emergence of certain heat-tolerant bacteria and raise the synthesis of their extracellular polysaccharides, as well as increased replication and altered transmission patterns of phytopathogenic viruses [31]. Changes in relative humidity patterns, such as increased precipitation or prolonged dry periods, can favor or reduce the development of plant pathogens [13,32,33]. Furthermore, extreme climate events like storms, hail, and floods can damage plants, facilitating pathogen entry and helping their spread via water and wind.

Climate change influences plant resilience and plants' sanitary status, impacting their susceptibility to plant pathogens. Higher temperatures hasten the growth of bacteria and fungus, which increases the prevalence of disease [31]. As they multiply in warmer climates, heat-adapted bacteria such as *Burkholderia glumea* are becoming more dangerous pathogens. Plant physiology may be impacted by elevated CO_2 concentrations, which may weaken their defensive mechanisms, but increased CO_2 may also alter the efficacy of particular pathogens [31]. Numerous diseases that were previously limited to warmer locations are now reported in new areas due to the expansion of the geographical range of numerous pathogens caused by climate change [34,35]. Increasingly frequent extreme weather events may facilitate the spread of diseases and worsen their management [34]. The variations in the timing of plant growth and growing seasons may result in host plant and pathogen mismatches and increase or decrease the disease pressure. Moreover, alterations in biodiversity and the makeup of microbial communities resulting from climate change can impact the equilibrium of beneficial and detrimental organisms, thereby affecting overall disease dynamics. As climate change advances, understanding and addressing its effects on plant diseases will be essential for sustaining crop yields and assuring food security [31].

3. Plant Pathogens Control

3.1. Physical Techniques

Physical environmentally friendly techniques (Figure 2) play an important role in managing plant pathogens by utilizing non-chemical techniques that manipulate the environment to reduce or eliminate pathogen populations [36]. These methods are eco-friendly and sustainable, and they can be integrated with other management strategies for desired results [37].

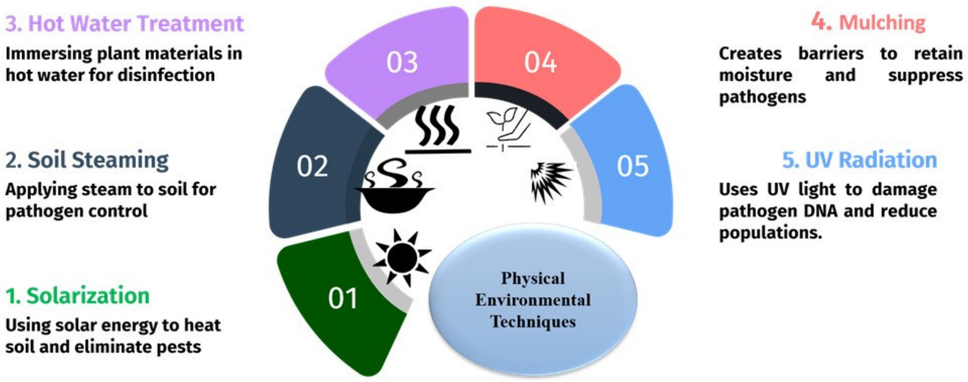

Figure 2. Physical management practices used for the control of plant pathogens.

3.1.1. Solarization and Soil Heating

Solarization is an environmentally friendly technique in which solar energy is used to heat the soil to reduce soil-borne pathogens, weeds, and pests [38]. This method involves covering the soil with transparent polyethylene sheets during the hottest months, usually summer [39]. The transparent film allows short-wave solar radiation to penetrate the soil while preventing the escape of longer-wavelength radiations, creating a greenhouse effect. The trapped heat raises the temperature of the soil to a level that is lethal to many pathogens and pests such as bacteria, fungi, and nematodes [36]. The elevated temperatures directly damage pathogen cellular structures through protein denaturation, enzyme inactivation, and the disruption of cell membranes [40]. Solarization includes changes in soil microbial communities, often favoring thermotolerant beneficial microorganisms that can further suppress pathogens through competition and antagonism [41]. Recent studies have shown that solarization can increase the soil temperature to 40–55 °C at depths of up to 15 cm, depending on the climatic conditions [42,43]. For example, the effectiveness of solarization in reducing *F. oxysporum* f.sp. *conglutinans* on rocket shows a significant reduction in disease outbreaks when combined with organic amendments [44].

Typically conducted in the summer, this process raises soil temperatures to levels that destroy many harmful pathogens, nematodes, and weed seeds or seedlings. It is a safe method that leaves no toxic residues and can be applied at both small and large scales. Soil solarization enhances soil structure and increases nitrogen availability and other vital plant nutrients. Soil pests are effectively killed at temperatures exceeding 30–33 °C [45]. However, plant pathogens, weeds, and other soil-borne organisms vary in their sensitivity to heat. This method eradicates or reduces several soil-borne pathogens, such as *Verticillium dahliae*, *F. oxysporum*, *Pythium ultimum*, and *Agrobacterium* spp., *Phytophthora cinnamomi*, *Sclerotium rolfsii*, and *Rhizoctonia solani* [46,47]. Soil heating by other means such as steam treatment is also used to control pathogens [48]. Despite so many benefits in soil pathogen control, there are some limitations/disadvantages to using the soil solarization process effectively in many regions. Soil solarization efficacy varies dramatically between tropical, temperate, and arid regions; for example, temperate regions lack sufficient solar radiation or experience frequent cloud cover as compared to tropical regions [49,50]. The economic feasibility of soil solarization presents challenges for many farmers, particularly small-scale operations where initial investment in plastic sheets and the labor costs associated with proper installation may be prohibitive [51].

3.1.2. Soil Steaming

This technique involves using steam generated from burning fuel to transfer heat to the soil or substrate, raising it to pasteurization or sterilization temperatures. Steam at low pressure exceeds 100 °C, releasing significant energy as it condenses into water and effectively heating the soil with minimal moisture. The high-temperature steam penetrates soil particles, killing pathogens through the thermal denaturation of proteins and nucleic acids, the disruption of cell membranes, and the degradation of cytoplasm [52]. Unlike solarization, which creates a temperature gradient in the soil profile, steam treatment can achieve more uniform heating throughout the treated depth, providing more consistent pathogen control [53]. First introduced in Germany in 1888, it served as the primary technique for soil disinfection before the advent of soil fumigants. Pasteurization requires a higher temperature (100 °C). In areas where solarization is not useful for the purpose, soil steaming can be the alternative option [54]. According to Panth et al. [36], soil steaming at a temperature above 70 °C for 30 min can eradicate common soil-borne pathogens like *Pythium* and *Verticillium*. In agriculture, soil steaming is generally treated as a pasteurization method, with recommended temperatures of 71 °C for 30 min to eliminate most pathogenic fungi, bacteria, and nematodes, and 83 °C for 30 min to target resistant weed seeds. The use of a mobile steam applicator has also been practiced to improve strawberries yields in California and control root-knot nematode in cut flower production in Florida [55].

3.1.3. Hot Water Treatment and Thermal Inactivation

Hot water treatment is a widely used method for disinfecting plant materials such as bulbs, seeds, and cuttings [56]. This technique involves immersing plant materials in hot water at a specific temperature for a certain period, which inactivates pathogens without damaging plant tissues [57,58]. The mechanism relies on the differential thermal sensitivity between host tissue and pathogen cells. Most plant pathogens are inactivated at temperatures that can be tolerated by dormant plant tissues, creating a therapeutic window for treatment [59]. Heat causes protein denaturation, membrane disruption, and enzyme inactivation in pathogen cells, while dormant plant tissues can withstand these temperatures without significant damage to their cellular structures. The key to success is precise temperature control and timing to exploit this difference in thermal sensitivity [60]. Recent research has focused on optimizing temperature and exposure times to maximize pathogen control while minimizing damage to the host plant [61–63]. For instance, treating tomato seeds at 50 °C for 25 min or rice seeds at 60 °C for 2 min effectively reduced bacterial and fungal pathogens without affecting seed germination rates [57,64]. Thermal inactivation can also be applied to irrigation water, compost, and other substrates to reduce the pathogen load [65]. Studies have shown that heating irrigation water to 60 °C for 20 min significantly reduces the presence of *Phytophthora* species, a common water-borne pathogen in horticultural systems [2,66].

3.1.4. Mulching

By creating a physical barrier on the soil surface, mulching will further retain soil moisture and regulate temperature. Mulching controls plant pathogens through multiple mechanisms. Physically, it prevents soil splashing that would otherwise transport soil-borne pathogens to aerial plant parts during rainfall or irrigation [67]. The barrier also prevents direct contact between plant tissues and soil-borne pathogens. Biologically, mulches (especially organic types) foster diverse microbial communities that compete with or antagonize pathogens through antibiosis, hyper-parasitism, and induced systematic resistance in host plants [68,69]. Many organic mulches release antimicrobial compounds during decomposition that can directly inhibit pathogen growth. Modified soil temperature and moisture regimes under mulches often create conditions less favorable for pathogen development but more conducive to beneficial microbial growth [36]. This will significantly improve soil properties, support microbial diversity, and suppress plant pathogens, contributing to healthier crops. Biodegradable mulches, such as straw and wood chips, decompose over time, enriching the soil with organic matter, further fostering microbial activity, and improving the soil health status. Mulching also suppresses plant pathogens by reducing soil splashing and promoting beneficial microbes that compete with or inhibit harmful pathogens. The effectiveness of mulching varies with the type of mulch and site-specific conditions, making tailored applications crucial. By leveraging mulching as a sustainable practice, farmers can improve soil health, reduce disease incidence, and enhance agricultural productivity [70].

3.1.5. Ultraviolet (UV) Radiation Treatment

UV radiation, particularly in the UV-C spectrum (200–280 nm), damages pathogen DNA by inducing the formation of pyrimidine dimers, which disrupts cellular function and reproduction [71]. The controlled application of UV radiation can effectively reduce pathogen populations on plant surfaces, seeds, and postharvest products without chemical residues. Recent developments in UV technology have led to the creation of automated systems that can treat large volumes of plant material or growing spaces with precise UV dosages [72]. Studies have demonstrated that pulsed UV treatments can effectively control powdery mildew in greenhouse crops and extend the shelf life of postharvest fruits by inhibiting fungal decay organisms [73]. The main advantages of UV treatment include its non-residual nature, compatibility with organic production systems, and potential for automation in controlled environment agriculture.

3.1.6. Practical Challenges and Limitations of Physical Techniques

Despite their environmental benefits, physical techniques for plant pathogen control face several practical challenges and limitations (Figure 3).

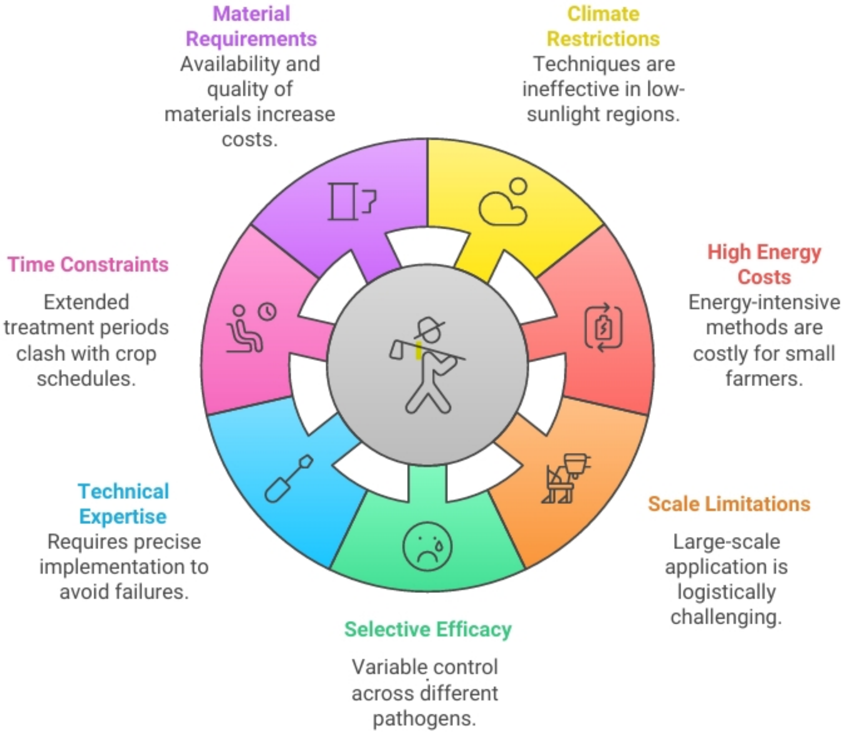

Figure 3. Infographic showing the challenges and limitations of physical techniques in pathogen control.

a. Climate and geographic restrictions: Soil solarization's effectiveness is highly dependent on local climate conditions, making it unsuitable for regions with limited solar radiation or shorter growing seasons. In temperate or cloudy regions, the soil may not reach the temperatures necessary for effective pathogen control [74].

b. Energy costs: Methods such as soil steaming and hot water treatment require significant energy inputs, making them economically challenging for small-scale farmers or in regions with high energy costs. The carbon footprint associated with these energy-intensive methods may partially offset their environmental benefits [75].

c. Scale limitations: Many physical techniques are more feasible at small to medium scales and become logistically challenging and costly for large-scale agricultural operations. For example, soil steaming in large field areas requires specialized equipment and significant resources [76].

d. Selective efficacy: Physical methods often provide variable control across different pathogen types. While some pathogens are highly susceptible to heat treatments, others, such as certain heat-resistant bacterial spores or deeply situated nematodes, may survive the treatment [77].

e. Technical expertise: The proper implementation of physical techniques often requires technical knowledge and precision. Incorrect application, for example, improper temperature or duration in hot water treatment, can either fail to control pathogens or damage the treated plant material [78].

f. Time constraints: Many physical techniques, particularly solarization, require extended treatment periods (4–6 weeks), which may not fit within tight crop rotation schedules or be economically viable for high-value cropping systems [79,80].

g. Material requirements: The quality and availability of materials, such as appropriate polythene films for solarization or suitable mulching materials, can limit implementation in certain regions or increase costs significantly [81,82].

3.1.7. Drawbacks or Potential Negative Impacts of Physical Techniques

Physical techniques that are generally considered environmentally friendly can still lead to some unintended negative impacts that are explained below (Figure 4).

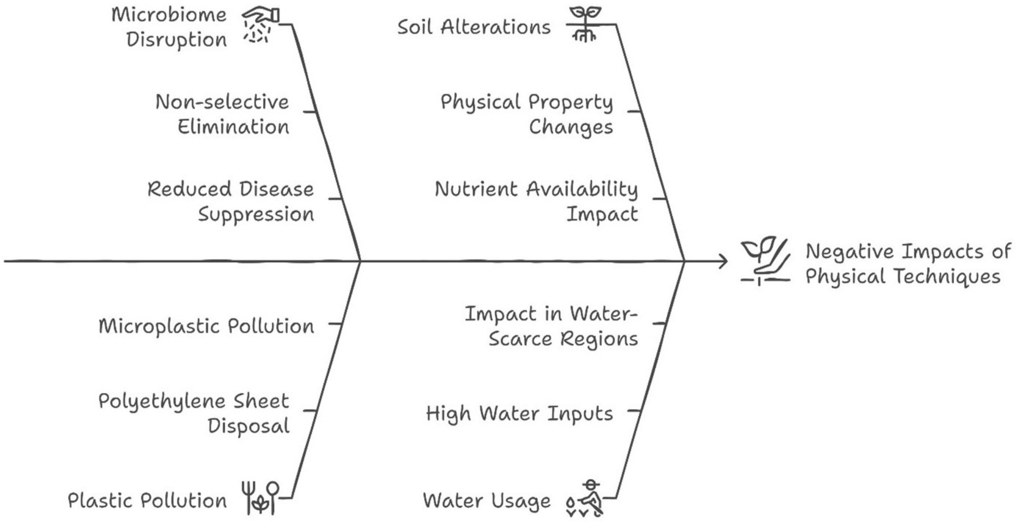

Figure 4. Infographic showing negative impacts of physical techniques in pathogen control.

a. Microbiome disruption: Heat-based methods like solarization and steaming can eliminate beneficial soil microorganisms and pathogens, potentially disrupting soil ecological balance[36]. This non-selective elimination may reduce natural disease suppression and soil health in the long term [83].

b. Plastic pollution: Soil solarization typically relies on polyethylene sheets, which, if not properly disposed of or if fragmented during use, can contribute to microplastic pollution in agricultural soils. The environmental impact of plastic mulches remains a significant concern [84,85].

c. Recolonization vulnerability: sterilized or pasteurized soil creates an ecological vacuum that can be rapidly recolonized by pathogens if reintroduction occurs, sometimes leading to more severe disease outbreaks than in untreated soils that maintain competitive microbial communities [86].

d. Physical soil alterations: High-temperature treatments can alter soil physical and chemical properties, potentially affecting soil structure, organic matter content, and nutrient availability. These changes may positively or negatively impact subsequent crop growth [87,88].

e. Water usage: some physical techniques, particularly hot water treatment and certain mulching practices, require significant water inputs, which may be problematic in water-scarce regions [54].

f. Selection pressure: the repeated use of physical control methods can potentially select for heat-resistant pathogen strains over time, though this has been less documented than resistance to chemical control [89].

g. Phytotoxicity risks: the improper application of heat treatments can cause phytotoxicity for plants or seeds, potentially reducing germination rates, vigor, or yields [90].

3.2. Cultural and Ecological Management Techniques

3.2.1. Crop Rotation and Diversification

Crop rotation—defined as the sequential cultivation of different crops on the same field—is one of the oldest and most effective environmentally friendly strategies for managing plant diseases, especially those caused by soil-borne pathogens [91]. Its effectiveness is primarily attributed to the ability of rotations to interrupt pathogen life cycles by alternating host crops with non-hosts or less susceptible species, thereby reducing the accumulation of inoculum in the soil [92–94]. Numerous field studies have demonstrated the success of this approach. For example, Larkin et al. [95] showed that long-term rotation trials in potato systems incorporating *Brassica* break crops such as canola or rapeseed have consistently reduced the incidence of soil-borne diseases including *Rhizoctonia* canker, black scurf, and common scab by 20–40%, with corresponding yield increases. Further, the addition of cover crops, such as winter rye, enhances these effects by improving microbial activity and soil suppressiveness [95,96]. Furthermore, the incorporation of biofumigant crops like mustard can also directly suppress fungal pathogens through the release of allelopathic compounds [97].

The effectiveness of crop rotation in disease management is highly dependent on the biological characteristics of the target pathogen [98,99]. For instance, Shennan et al. [100] demonstrated that rotation is particularly successful against soil-borne pathogens with narrow host ranges and limited survival structures, such as *Verticillium dahliae*, with notable disease suppression observed when non-host crops like untreated lettuce were introduced into strawberry cropping systems. In contrast, rotation is far less effective against pathogens with broad host ranges or long-lived survival structures, such as *Sclerotinia sclerotiorum*, which can persist in the soil as sclerotia and evade disruption through rotational practices [36]. Similarly, foliar pathogens—particularly those dispersed over long distances by wind, like rust fungi—are typically unaffected by local crop rotations unless they rely on overwintering in crop residues or adjacent vegetation to complete their life cycles [101].

Comparative research across different agroecosystems reinforces the broad applicability of rotation as a disease management tool [102]. This is particularly evident in low-input and organic systems, where crop diversification—often implemented through rotation—is a cornerstone strategy for managing plant diseases in the absence of synthetic chemical controls. For example, in African smallholder systems, rotating maize with legumes or fallow has been associated with a lower incidence of root rots and parasitic nematodes, along with improved soil fertility [103,104]. In contrast, intensive systems such as the corn–soybean rotation dominant in the United States may offer limited pathogen suppression, as pathogens like *Fusarium* spp. and *Pythium* spp. can persist due to overlapping host susceptibility [105,106]. Furthermore, in European cereal systems, more diversified rotations, especially those exceeding two years, have been shown to reduce foliar disease severity and consequently reduce the need for fungicide applications [101]. Additionally, crop rotational diversity has been shown to enhance the disease-suppressive capacity of soil microbiomes by shaping bacterial community composition and increasing the abundance of functional groups that produce antifungal compounds [107,108]. Importantly, while overall microbial diversity may not always increase, it is the structure and functional potential of the microbial community that plays a more critical role in effective pathogen suppression [109,110].

Despite its strengths, crop rotation faces limitations. It is less applicable to perennial cropping systems where replanting occurs infrequently, although cover crops and rotation during replanting cycles can offer some control. For instance, fields previously infested with *Fusarium oxysporum* causing Panama disease in banana must be rotated out of bananas for many years to reduce pathogen pressure, a practice not always feasible due to land constraints or market demands [111–114]. Additionally, economic pressures in high-value agriculture may favor monoculture over more sustainable rotational practices [93].

Crop rotation and diversification are versatile, environmentally friendly tools that can significantly reduce the prevalence of soil-borne diseases and enhance soil health. However, their effectiveness is context-dependent, varying with pathogen ecology, crop choices, and management constraints. Integrating rotation with other disease management strategies enhances its reliability and long-term benefits. Crop rotation advantages and limitations are summarized in Table 1.

Table 1. Summarized aspects of crop rotation.

Advantages	Disadvantages/Limitations
Significantly reduces inoculum build-up of many soil-borne pathogens by breaking the host cycle (e.g., less *Verticillium* wilt and common scab under rotations) [95]	Ineffective against pathogens with broad host ranges or long-lived resting spores that survive between crops (e.g., *Sclerotinia* spp., *Verticillium* in short rotations) [95]
Can lower disease pressure in subsequent crops, often translating to yield benefits and reduced need for chemical controls [95]	Requires availability of suitable alternative crops; may not be economically attractive if break crops have lower market value or if land is limited [115]
Improves overall soil health and microbial diversity, which can induce suppressiveness to pathogens over time [101,116]	Not a rapid solution—benefits accrue over multiple seasons, while some diseases might still occur at low levels, necessitating additional measures for full control [117]
Suited to organic and low-input systems as a cost-effective, non-chemical disease management strategy [102]	Limited applicability in perennial cropping systems and in regions with highly specialized monocultures; logistical and management challenges in diversifying crop rotations in intensive farming [118,119]
Can be combined with cover crops or biofumigant crops to enhance pathogen suppression (e.g., mustard cover crops release biocidal compounds) [120]	Does little to prevent airborne or polycyclic foliar diseases that re-infest from outside sources each season [101]

3.2.2. Sanitation and Residue Management

Biofumigation

Biofumigation is a promising, environmentally friendly alternative for managing plant pathogens, particularly soil-borne diseases, by using biocidal compounds released from specific plant materials [121,122]. This method leverages the hydrolysis of glucosinolates found in *Brassica* species to produce isothiocyanates, which exhibit nematicidal and fungicidal properties [123–127]. Biofumigation has demonstrated significant efficacy against various soil-borne pathogens, such as *F. oxysporum* and *R. solani*, with suppression rates exceeding 60% in some cases [128]. Other studies showed that shredded plant materials from species such as Indian mustard, brown mustard, turnip (*Brassica rapa*), and radish (*Raphanus sativus*) release volatile sulfur compounds that effectively inhibit soil-borne pathogens affecting potatoes, including *R. solani, Phytophthora* spp., *P. ultimum*, and *S. sclerotiorum* [129]. For example, Indian mustard achieved an 80–100% inhibition of potato pathogens in Petri dishes at 25 °C, while black mustard (*B. nigra*) applied at 5% *w*/*w* reduced *R. solani* colonization by 75%, with effects lasting up to six months [130]. Other *Brassica* species, such as *B. integrifolia* and *B. oleracea* var. *gongylodes*, also showed strong inhibitory effects on *Pythium* and *Fusarium* species under similar conditions [131]. In addition to reducing dependence on synthetic pesticides [132], biofumigation can enhance soil fertility and stimulate beneficial microbial communities, such as *Streptomyces* [133], *Actinobacteria* [134], and arbuscular mycorrhiza fungi [135,136], contributing to overall soil health [137]. Nevertheless, studies on the effect that biofumigation may have on soil microbes show mixed results. While some reported increased microbial diversity [138], others noted declines [139], likely due to differences in materials, application rates, and conditions—highlighting the need for further research.

However, while biofumigation offers several advantages, it also faces notable challenges, such as seasonal limitations, as the availability of suitable plant biomass for biofumigation can be restricted during off-seasons [121]. In addition, the effectiveness of biofumigation can vary based on soil conditions, the plant species used, and the number of active compounds produced, as well as environmental factors, necessitating further research to optimize practices [121,137,140,141]. Furthermore, studies also suggested that the suppressive effect of biofumigant plants on pathogens is often temporary, gradually declining, rather than providing permanent control [131] and meanwhile inadvertently reducing populations of beneficial entomopathogenic nematodes [142]. Further research is required to understand how harmful soil organisms recover after biofumigation and how long its effects last. Moreover, under challenging conditions like drought, biofumigation alone may not enhance yields, highlighting the need to combine it with other sustainable practices for lasting disease control [143].

Despite its potential, the effectiveness of biofumigation can be inconsistent, and further research is needed to refine techniques and enhance its application in diverse agricultural contexts, including while other biofumigant sources are used. Plants belonging to the *Liliaceae, Gramineae, Compositae*, and *Leguminosae* families showed similar benefits [137,144].

Anaerobic Soil Disinfestation

Anaerobic soil disinfestation (ASD), also cited as reductive soil disinfestation, biological soil disinfestation, anaerobically mediated biological soil disinfestation, and soil reductive sterilization, presents both advantages and challenges in managing plant pathogens [145,146]. This method, which involves amending soil with easily decomposable organic matter, saturating it with water, and covering it to create anaerobic conditions for up to 3 weeks, has shown promise in suppressing soil-borne pathogens and pests [147–149].

However, its effectiveness can vary, based on environmental conditions and specific pathogen types. ASD has been shown to effectively suppress various soil-borne pathogens, including nematodes, bacteria, and fungi (i.e., *Agrobacterium tumefaciens*, *R. solanacearum*, *Colletotrichum coccodes*, *F. oxysporum*, *Phytophthora capsici*, *S. sclerotiorum*, and *Pratylenchus penetrans*), through the production of organic acids and volatile compounds under anaerobic conditions [150–157]. Ueki et al. (2018) [158] have demonstrated the efficient management of soil-borne pathogens through the activity of anaerobic bacteria such as *Clostridium beijerinckii*, which produce antifungal enzymes. Anaerobic soil disinfestation offers a sustainable, chemical-free alternative to conventional soil fumigation, making it well suited for organic agriculture and areas with strict pesticide regulations. This method can also be combined with other eco-friendly strategies, such as crop rotation, biological control agents, and organic amendments, for integrated disease management [155,159]. The process can lead to significant shifts in soil microbial communities, potentially enhancing soil health and disease suppression in subsequent cropping systems [155,160]. In this context, Hewavitharana et al. (2019) [161] described three microbial phases during ASD, marked by shifts in dominant microbial groups, as follows: in the first phase, aerobic and facultative organisms such as *Bacillus, Pasteuria, Streptomyces, Pseudomonas*, and *Ascomycota* fungi prevail. As oxygen depletes, the second phase sees a rise in facultative anaerobes from *Firmicutes, Actinobacteria, Proteobacteria*, and *Zygomycota*, with *Bacillus* spp. being strongly associated with lactic acid production. In the final phase, strict anaerobes like *Clostridium* spp. dominate, producing bioactive compounds that suppress pathogens [161]. In addition, ASD may lead to the recovery of several biocontrol agents (i.e., *Bacillus* spp., *Trichoderma* spp., *Streptomyces* spp., *Coniothyrium minitans*, and *Chaetomium* spp.) [153,156,162,163]. However, exploring the use of biocontrol agents to recolonize soils following ASD treatment is a promising strategy that warrants further research.

The type of carbon source applied in anaerobic soil disinfestation (ASD) significantly influences the structure of the soil microbial community [154,164,165]. When ethanol—a readily degradable carbon source—is used, it promotes the proliferation of *Firmicutes* species, while using alfalfa meal, a more resistant and complex carbon source, favors microbial groups from *Firmicutes*, *Bacteroidetes*, and *Proteobacteria* [166]. In addition, in a recent study, Duan et al. [167] emphasized the effectiveness of reductive soil disinfestation (RSD), especially when paired with targeted organic amendments, in controlling soil-borne pathogens and reducing high-risk antibiotic resistance genes (ARGs). This effect is largely mediated through shifts in soil microbial communities, particularly *Actinobacteria*, as well as changes in mobile genetic elements and soil total nitrogen. Supporting these findings, Chen et al. [168] also demonstrated that ASD significantly lowers the abundance of multiple ARGs. However, Chen et al. [169] reported that ASD can lead to a 4.1% increase in potential human pathogenic bacterial (HPB) species and a 23% rise in related genes. These shifts in bacterial community dynamics under ASD may enhance interactions between HPB and non-pathogenic microbes, potentially promoting the dissemination of resistance genes [169].

Despite its potential, the ASD technique meets challenges concerning its effectiveness, which can differ significantly based on soil type, carbon source, and environmental conditions, leading to inconsistent results [159,160]. Likewise, the complexity of implementing the ASD technique requires the careful management of soil moisture and temperature, as well as the selection of appropriate organic amendments, which can complicate its adoption in commercial settings [155,157]. Challenges may also involve optimizing conditions for anaerobiosis and ensuring consistent efficacy across different soil types [158]. While promising, the mechanisms behind the efficacy of ASD are not fully understood, necessitating further research to optimize its application and improve reliability [155,157].

In addition, the duality of ASD regarding soil ARG dynamics underscores the need for careful management practices in agricultural settings.

Intercropping and Mixed Cropping Systems

Intercropping—the simultaneous cultivation of two or more crop species in the same field—is a spatial diversification strategy with demonstrated potential to suppress both foliar and soil-borne plant pathogens [170]. Unlike crop rotation, which relies on temporal separation, intercropping modifies the cropping environment in real time by altering plant architecture, microclimate, and host spatial distribution [171]. This spatial heterogeneity is often unfavorable for pathogens and can significantly disrupt their transmission dynamics [172]. In this regard, a comprehensive review of over 200 studies found that disease incidence was reduced in approximately 73% of intercropping trials compared to monocultures, with the most consistent benefits observed for foliar fungal pathogens [172]. Several mechanisms highlight this protective effect. As inferred by Civitello et al. (2015) [173] and later by Chadfield et al. (2022) [174], host dilution reduces the density of susceptible plants, thereby limiting pathogen spread. Diverse canopies can hinder the wind and rain-splash dispersal of spores, while complex vegetation structures may alter humidity and temperature, reducing conditions favorable for infection [172,175]. In addition, Zhu et al. (2000) [175] demonstrated that planting mixtures of genetically diverse rice varieties significantly reduced the incidence of rice blast disease by 94%, primarily due to canopy-mediated spore interception and microclimate changes. Thus was highlighted the effectiveness of intercropping strategies in disease management. Moreover, plant–plant interactions at the physiological or biochemical level may contribute to disease suppression, including the induction of host defenses or allelopathic effects on pathogens in the rhizosphere [176,177]. Additionally, certain legume–cereal intercrops have been shown to enhance soil microbial diversity and suppressiveness, thereby further contributing to disease control [178,179]. Field studies confirmed that intercropping can be effective against a range of pathogens. In this regard, Wu et al. (2024) [180] and Zhang et al. (2019) [181] reported that cereal–legume intercropping systems often lead to reduced severity of foliar diseases such as powdery mildew and rust, largely due to canopy disruption and associated microclimatic effects. Similarly, in tropical smallholder systems, traditional combinations such as maize–bean or sorghum–pigeonpea have been shown to reduce leaf lesions and slow disease spread, likely by interrupting the continuous presence of susceptible hosts [172]. Soil-borne pathogens and nematodes also respond positively: in a meta-analyses based study, Chadfield et al. (2022) [174] showed average reductions of 55% in soil-borne disease and 40% in nematode damage across intercropped systems. Nonetheless, intercropping does not always yield positive outcomes; in approximately 27% of cases, the disease incidence remained unchanged or even increased—often due to incompatible crop combinations that result in dense, humid canopies conducive to foliar pathogen development [172,182].

Intercropping is particularly relevant for smallholder and organic systems, where it provides both agronomic and socio-economic benefits. For resource-limited farmers without access to fungicides, strategic intercrops can reduce disease pressure while offering yield stability through diversified outputs. In contrast, mechanized, large-scale agriculture has historically avoided intercropping due to equipment and market constraints. However, recent studies in high-input systems in Europe and North America are revisiting intercropping as a sustainable strategy. For instance, the strip-intercropping of oilseed rape with peas reduced *Sclerotinia* incidence in rape and rust in the legume, suggesting multi-pathogen control potential [183].

Despite its many advantages, intercropping also poses significant challenges. Managing multiple species with different agronomic needs requires the careful coordination of planting, harvesting, and input use, often increasing management complexity. Limitations in machinery, logistical hurdles associated with marketing diverse crops, and potential interspecies competition for light, water, or nutrients can further complicate implementation. From a plant health standpoint, there is also the risk of exacerbating disease pressure—particularly if both crops share susceptibility to the same pathogens or if intercrops serve as alternate hosts (e.g., grasses supporting rust life cycles). As such, successful intercropping relies on a deep understanding of crop–pathogen interactions and thoughtful system design.

Overall, when properly implemented, intercropping offers a robust, cost-effective strategy for managing multiple plant pathogens while enhancing agroecosystem resilience [184]. Its success is highly context-dependent but supported by a growing body of field-based evidence across diverse cropping systems. The summarized advantages and challenges of intercropping are presented in Table 2.

Table 2. Summarized aspects of intercropping.

Advantages	Disadvantages/Limitations
Reduces disease incidence in many systems by diluting host presence and impeding pathogen spread (e.g., 73% of studies show lowered foliar disease in intercrops) [172]	Added management complexity—requires coordinating different crops' agronomy (sowing, harvest, fertilization) and often complicates mechanized farming operations [185]
Can target multiple pest types simultaneously: certain intercrops suppress diseases, insect pests, and weeds at once, offering holistic protection [186,187]	Risk of competition between intercrop components for light, nutrients, or water, which can reduce the yield of the main crop if not properly managed [188]
Often highly effective against foliar fungal diseases due to altered microclimate and physical barrier effects—e.g., significantly lower rust and leaf spot severity in cereal-legume mixtures [172]	If both crops share a susceptibility to a pathogen, disease can spread on both (poor intercrop pairing can inadvertently increase total host area for a pathogen). Proper selection of complementary crops is essential [172]
Provides greater yield, stability and resilience: even if one crop is hit by disease, the other crop can still yield, buffering total production [175,189,190]	Adoption barriers in large-scale conventional farming—market logistics for multiple crops and lack of compatible machinery make farmers hesitant to adopt intercropping widely [191]
Low input cost strategy suitable for resource-poor farmers (no need for purchased inputs), and compatible with organic farming principle [179,192]	Requires knowledge and careful planning. Site-specific research and farmer training are needed to implement successful intercropping designs that truly confer disease protection without undue trade-offs [193]

3.3. Use of Resistant Cultivars

The deployment of disease-resistant cultivars is widely recognized as one of the most effective and environmentally friendly strategies for managing plant diseases [194]. By incorporating genetic resistance into crops, this approach enables plants to defend themselves against pathogens, minimizing the need for chemical controls and reducing yield losses [101,195]. Resistance may be qualitative (conferred via single major genes) or quantitative (involving multiple genes), with the former often providing complete resistance to specific pathogen races and the latter offering partial but more durable protection across diverse pathotypes [195,196]. The success of breeding programs in developing resistant varieties is well documented across both temperate and tropical regions [197,198]. For instance, the introduction of stem rust-resistant wheat lines has averted major epidemics in high-risk areas [199], while downy mildew-resistant pearl millet in India led to higher yields and resolved a long-standing disease challenge [200]. Similarly, in Africa, resistant cassava cultivars have successfully countered the Cassava Mosaic Virus, restoring productivity to severely affected regions [201]. Beyond conventional breeding, resistance has also been successfully deployed through horticultural techniques such as grafting, where susceptible scions are joined to resistant rootstocks—as in the case of watermelon grafted onto squash to manage *F. oxysporum* f. sp. *niveum* [202].

Host resistance plays a vital role in managing both soil-borne and foliar pathogens across a wide range of crops. For example, the development of lettuce cultivars resistant to *Verticillium* wilt [203], tomato lines resistant to *Ralstonia* [204] and *Fusarium* [205], and pea varieties resistant to *Aphanomyces* root rot [206] illustrates the effective application of genetic resistance to combat soil-borne diseases. In parallel, resistance to foliar pathogens such as rusts, blights, and mildews has been equally critical in protecting aboveground plant health [207]. Notably, Joobeur et al. [208] demonstrated that melon cultivars combining *Fom-2* for *Fusarium* resistance and *Pm-1* for powdery mildew resistance exemplify the potential of gene pyramiding to achieve broad-spectrum protection. These advances are consistently supported by multi-environment field trials, which showed that resistant genotypes contribute significantly to both disease suppression and yield stability [194,209].

Despite its proven benefits, host resistance is not without limitations—with one of the most significant being its long-term durability, particularly in the case of qualitative, single-gene resistance. As Brown [210] emphasized, pathogens with large, genetically diverse populations can rapidly adapt and overcome such resistance, resulting in the well-known ”boom-and-bust” cycles of disease control failure. A striking example comes from *Leptosphaeria maculans* in oilseed rape, where field populations overcame single-gene resistance within just three years; however, when combined with quantitative resistance, the effectiveness was maintained for a longer period [211]. This ongoing evolutionary arms race has rendered many formerly effective resistance genes ineffective over time, especially in cereal crops, where rust populations shift rapidly [212]. In response, breeding and management strategies such as gene pyramiding, cultivar rotation, and the use of varietal mixtures have been employed to extend resistance durability. For instance, wheat varietal mixtures containing diverse rust resistance genes have been shown to reduce epidemic severity and slow the emergence of virulent pathogen races [213]. Similarly, in Chinese rice systems, deploying mixtures of resistant and susceptible cultivars significantly reduced the blast incidence while preserving the long-term effectiveness of resistance genes [175].

While host resistance remains a fundamental component of plant disease management, several practical challenges continue to limit its widespread adoption. A major limitation is the specificity of resistance, which is typically effective against a single pathogen but offers no protection against others—for example, a tomato cultivar resistant to *Fusarium* wilt may still be vulnerable to bacterial spot [214]. Additionally, resistance traits can sometimes be linked to agronomic drawbacks, such as a lower yield or compromised fruit quality, though ongoing advances in breeding technologies are helping to overcome these limitations [215,216]. Another issue relates to unequal availability: minor and less-commercialized crops often receive limited breeding investment, and smallholder farmers may struggle to access resistant varieties due to affordability or distribution challenges. Looking ahead, transgenic and genome-edited resistance represent promising technological developments. However, their implementation remains restricted due to regulatory constraints and societal acceptance—particularly within organic agriculture. For instance, despite showing resistance to Huanglongbing, gene-edited citrus varieties have not yet reached commercial deployment due to regulatory delays [210].

Nevertheless, despite these limitations, host resistance continues to serve as a key element in plant disease management. Its value is particularly evident within integrated approaches, where it works synergistically with other strategies such as crop rotation, biological control, and targeted fungicide use. In many cropping systems, resistant cultivars form the first line of defense, providing farmers with a proactive and cost-effective tool to manage both endemic and emerging plant pathogens. The summarized advantages and limitations of resistant cultivar use are presented in Table 3.

Table 3. Summarized aspects of the use of resistant cultivars.

Advantages	Disadvantages/Limitations
Can provide high efficacy disease control with little to no additional cost or effort during the season—the resistance is built into the plant (e.g., resistant varieties often suffer minimal yield loss under heavy disease pressure) [217,218]	Pathogen populations can evolve to overcome genetic resistance, especially single-gene (vertical) resistances, leading to potential breakdown of control within a few seasons if not managed [210,219–221]
Environmentally friendly and compatible with all farming systems (conventional and organic)—reduces the need for chemical fungicides and other inputs [101,218,222,223]	Breeding and delivering resistant varieties take time and resources. There can be a lag in availability for certain crops or emerging diseases, and minor crops may lack resistant options due to limited breeding programs [224–226]
Often the most cost-effective strategy: farmers typically pay the same (or only slightly more) for resistant seed, but avoid major losses—e.g., virus-resistant cassava and downy mildew-resistant millet dramatically improved yields for smallholders [227–229]	Resistance is usually disease-specific—a variety resistant to one pathogen may still require management of other diseases. No cultivar is immune to all threats, so farmers may need multiple resistant varieties or other controls for a full protection spectrum [230–232]
Can be combined (pyramided) to address multiple diseases in one cultivar (e.g., modern tomato hybrids with resistance to wilt, nematodes, virus, etc.), thereby simplifying disease management for growers [233–235]	Potential trade-offs: in some cases, resistance genes might be linked with less desirable agronomic traits, possibly affecting yield or quality. Farmers might be hesitant to adopt a new resistant variety if it differs in taste or market preferences from traditional ones [215,236–238]
Proven track record of preventing crop epidemics and stabilizing production—for example, rust-resistant wheat and coffee leaf rust-resistant coffee varieties have largely averted what would have been severe losses [239]	Over-reliance on resistance alone can be risky; if resistance breaks, growers can be left with little defense; best practices require integrating resistant cultivars with other strategies (rotation, crop diversification, etc.) to hedge against resistance breakdown [223,240–242]
Readily used in both high-input and low-input systems: high-input agriculture uses resistance to reduce spray programs, while low-input farmers rely on resistant landraces or improved varieties as a primary defense when chemicals are unaffordable [243–245]	Regulatory and acceptance issues for certain types of resistance—transgenic or gene-edited disease-resistant crops (e.g., virus-resistant papaya, late blight-resistant GM potato) could vastly improve control, but public concerns and regulations may restrict their deployment, delaying benefits to farmers (GMO debates) [246,247]

3.4. Soilless Culture

Soilless culture systems—including hydroponics, nutrient film techniques, and inert substrates such as rockwool, coco coir, and perlite—have become an increasingly effective environmentally friendly strategy for managing plant diseases, particularly by circumventing soil-borne pathogens [248]. Originally developed to combat soil fatigue and persistent pathogen pressure in high-value crops, these systems enable cultivation in a controlled, soil-free environment where many traditional pathogens are unable to persist [249,250]. By replacing contaminated soils with sterile growing media and delivering nutrients through precisely regulated solutions, growers are able to disrupt pathogen life cycles that rely on soil as a reservoir. As a result, soilless systems have gained widespread adoption in the greenhouse cultivation of crops such as tomatoes, cucumbers, strawberries, and lettuce [251].

Their primary advantage lies in the effective exclusion of soil-borne pathogens, including *Verticillium* spp., *Fusarium* spp., and root-knot nematodes, which are otherwise difficult to manage in conventional systems [252]. For instance, strawberry growers using substrate-based systems report a marked reduction in *Verticillium* wilt incidence compared to field-grown production [249]. Similarly, greenhouse tomato cultivation in rockwool or coir minimizes the occurrence of *Fusarium* crown and root rot—previously a major concern necessitating routine soil fumigation [250]. These outcomes underscore the core biosecurity advantage of soilless systems: sterile, disposable media prevent the long-term persistence and re-emergence of soil-borne pathogens [253]. Despite their advantages, soilless culture systems are not entirely free from disease risks [254].

While these systems effectively eliminate many soil-borne pathogens, they introduce new vulnerabilities—particularly to waterborne diseases caused by oomycetes such as *Pythium* and *Phytophthora*. Calvo-Bado et al. [255] demonstrated that these pathogens can enter hydroponic systems through contaminated water sources or infected transplants and spread rapidly via recirculating nutrient solutions. In closed-loop systems, the infection of a single plant can lead to systemic outbreaks of root rot unless rigorous sanitation protocols are in place. Additionally, pathogens like *F. oxysporum* may be introduced via infected seedlings and can persist and disseminate within the system through spore dispersal or biofilm formation [256].

Nevertheless, one of the key advantages of soilless culture lies in its capacity for containment and control: systems can be disinfected between growing cycles, and waterborne pathogens can be managed through technologies such as UV irradiation or ozone sterilization of nutrient solutions—practices that are far more challenging to implement in traditional field soils [248]. From a systems-level perspective, soilless cultivation is particularly well suited to high-value horticultural crops grown in intensive production environments, such as European greenhouse complexes and peri-urban vegetable farming operations [257]. Its adoption has expanded in part as a response to soil degradation and contamination, especially in regions where traditional fumigants like methyl bromide have been phased out due to environmental concerns [249,258]. Soilless systems offer several compelling advantages: they effectively prevent soil-borne disease outbreaks [249], enable full sanitation and system reset between crop cycles [258], integrate seamlessly with controlled environment agriculture [248], and eliminate reliance on soil fumigants [256]. Moreover, these systems support uniform plant growth, which facilitates disease monitoring and agronomic management [251].

However, their implementation is not without challenges. The high initial investment, technical complexity, and need for specialized knowledge can pose barriers to entry, particularly for small-scale growers. In addition, the closed-loop nature of most systems increases the risk of rapid disease spread if contamination occurs, and foliar pathogens may still thrive if environmental controls—such as humidity and air circulation—are not carefully managed [259]. Finally, regulatory hurdles can arise for growers seeking organic certification, as hydroponically grown produce may not qualify under certain national or regional organic standards, thus limiting access to organic markets. Table 4 summarizes the principal advantages and challenges of the soilless technique.

Table 4. Summarized aspects of soilless culture.

Advantages	Disadvantages/Limitations
Virtually eliminates many soil-borne disease problems by removing the crop from native soil (e.g., no build-up of wilt fungi or nematodes in a hydroponic system) [36,251,260,261]	High initial investment and technical expertise required—not economically feasible for low-value crops or many smallholders; primarily used in capital-intensive operations [250]
Allows continuous cropping without rotation or fallow, since clean substrate can be used each cycle; no need for soil fumigation or sterilization chemicals [257,262,263]	Pathogens can still enter via contaminated transplants or water and then spread rapidly in recirculating systems (e.g., *Pythium* root rot in hydroponics); demands rigorous sanitation and monitoring [264–266]
Highly controlled root environment—optimal nutrition and moisture can strengthen plant defenses and reduce stress-related disease susceptibility. Also easier to treat the root zone (e.g., sterilizing nutrient solution) if a pathogen is detected [264,267–269]	Does not inherently stop foliar diseases—greenhouse crops still face risks like powdery mildew or gray mold, requiring separate control measures. Dense plantings and stable environments can even favor some airborne pathogens if climate control falters [253,260,270,271])
Substrates (rockwool, coir, etc.) are typically pathogen-free to start, and can be steam-sterilized or replaced, preventing carryover of inoculum between crops. This resets the disease cycle in a way not possible in field soil [150,249,260,272,273]	Waste management and sustainability concerns—spent substrate and nutrient runoff must be handled properly. Closed systems need careful management to avoid phytotoxic accumulation or algal growth, which can indirectly introduce pathogens [274–277]
Proven success in greenhouse vegetable and berry production: dramatic reductions in soil disease losses and consistent high yields (e.g., substrate-grown strawberries largely avoid soil wilt issues, enabling production in infested areas) [251,278]	Limited scope of use—mostly confined to high-value crops and controlled environments. Not a practical solution for broadacre field crops or resource-limited farming communities without significant support and infrastructure [279–281]
Reduces reliance on chemical pesticides for soil pests, aligning with stricter environmental regulations (no need for methyl bromide, etc.), and can be combined with biological control in the nutrient solution to suppress any pathogen that appears (e.g., beneficial microbes in hydroponics) [253,254]	Some organic and consumer market barriers: hydroponic produce may not be accepted as "organic" under certain standards, and consumers might perceive soilless produce differently, which can influence growers' decisions in niche markets [282–285]

3.5. Biological Control Approaches

3.5.1. Microbial Inoculants as Biocontrol Agents

The exploration of novel microorganisms as BCAs has garnered increasing attention as a sustainable alternative to chemical pesticides in plant disease management. This approach aligns with the broader goals of environmentally friendly agriculture by leveraging naturally occurring microbial interactions to suppress plant pathogens.

Among the well-characterized bacterial genera, *Bacillus*, *Streptomyces*, and *Lysobacter* have shown considerable promise due to their ability exhibit a wide range of antagonistic activities against plant pathogens, including antibiosis, competition for nutrients and space, and the induction of plant systemic resistance [286,287]. *Bacillus* strains are identified as effective plant growth-promoting bacteria (PGPB) that serve as biocontrol agents against plant pathogens [288]. In particular, they are known for their prolific production of secondary metabolites such as lipopeptides, which not only inhibit pathogen growth but also enhance plant resilience through the induction of plant systemic resistance (PSR) [289]. *Bacillus subtilis* and *Bacillus megaterium* demonstrated significant suppression of *Fusarium graminearum*, a major wheat pathogen [290]. Some other bacterial strains, like *Pseudomonas aeruginosa* FG106, also induced PSR, enhancing their ability to fend off pathogens through the production of volatile compounds and biofilm formation [291]. Likewise, *Streptomyces* spp. have demonstrated strong antifungal activity against phytopathogens like *Fusarium* spp., largely attributed to their competitive behavior and production of antibiotics [292] *Lysobacter* enzymogenes has also emerged as an effective biocontrol agent, with studies highlighting its inhibitory effects on *Alternaria solani* and *F. oxysporum*, often outperforming conventional fungicides in controlled environments [293].

Similarly, beneficial fungi like *Trichoderma* spp. and mycorrhizal fungi have shown significant potential in suppressing root pathogens through the production of hydrolytic enzymes, mycoparasitism, and enhancement of plant stress tolerance [294]. In a comprehensive overview of biological control methods using beneficial microorganisms, Sarrocco [295] reviewed selected breakthroughs in biological control over the past 50 years, showcasing the role of *Trichioderma* isolates and mycoviruses that confer hypovirulence to plant pathogenic fungi. This innovative approach has shown promise in reducing the virulence of harmful fungi, thereby enhancing plant health and crop yields [296].

Arbuscular mycorrhizal fungi (AMF) also serve as biocontrol agents against plant-parasitic fungi and nematodes by competing for nutrients and space, altering rhizosphere interactions, and enhancing plant tolerance, thus providing an environmentally friendly alternative to synthetic chemical management methods [78]. For example, Bilgili, 2025, demonstrated the potential of AMF as biocontrol agents against plant pathogens. Species like *Funneliformis mosseae*, *Rhizophagus intraradices*, and *Claroideoglomus etunicatum* effectively reduced disease severity in pepper plants infected with *Fusarium solani* [297]. Similarly, *Glomus fasciculatum*, *G. mosseae*, and *Acaulospora laevis* reduced maize black bundle disease, with *G. fasciculatum* showing full suppression; they all improved plant growth, highlighting their dual role as biocontrol agents and growth promoters [298,299]. However, recent studies have emphasized the importance of strain specificity, environmental conditions, and microbial compatibility in determining the success of microbial inoculants in field applications [300]. While laboratory and greenhouse trials often report high efficacy, field performance can be inconsistent due to environmental fluctuations, microbial competition, and soil variability [286,301].

In parallel with these established genera, increasing efforts are being directed toward the identification and functional characterization of underexplored microbial species with biocontrol potential. For instance, *Clonostachys rosea* and *Lysobacter capsici* are currently under investigation for their activity against soil-borne pathogens, with preliminary studies yielding promising results [302]. Moreover, less conventional organisms such as *Bdellovibrio bacteriovorus*, a predatory bacterium that targets Gram-negative pathogens, and *Paenibacillus* spp., which are known to produce a range of antimicrobial and lytic enzymes, are gaining attention as potential sources of novel biopesticides [302]. These emerging taxa not only broaden the spectrum of biological control strategies but also offer opportunities to develop more targeted and ecologically compatible solutions.

Nevertheless, despite the growing body of evidence supporting the efficacy of microbial biocontrol agents, several challenges must be addressed to facilitate their widespread adoption. These include variability in field performance due to environmental influences, limitations in formulation stability and shelf-life, and regulatory complexities surrounding product registration and commercialization. Continued research into ecology, mechanisms of action, and application strategies of both established and emerging microbial taxa is, therefore, essential to fully realize their potential within integrated pest management systems. As the search for sustainable plant protection intensifies, microbial biocontrol remains a vibrant and evolving field with substantial implications for the future of crop health and environmental stewardship. The summarized aspects of BCAs application, including advantages and limitations, are presented in Table 5.

Table 5. Summarized aspects of BCAs' application.

Aspect	**Advantages**	**Limitations**
Environmental impact	Eco-friendly, reduces chemical pesticide use [303–307]	May be less effective in certain environmental conditions [308–314]
Specificity	Often targets specific pathogens, preserving beneficial microbiota [289,315–318]	Narrow spectrum may require multiple agents for broad protection [319,320]
Resistance management	Lower risk of resistance development compared to chemicals [321–324]	Pathogens may still develop tolerance over time [325–328]
Soil and plant health	Improves soil microbiome and plant growth (some PGPRs) [147,179,300,329–333]	May compete with native microbes, affecting performance [289,319,334,335]
Sustainability	Suitable for organic and integrated pest management (IPM) systems [320,336–341]	Requires more complex management and monitoring [317,320,342–344]
Residues	No harmful residues on crops [345–348]	Slower action may not be suitable for acute outbreaks [314,349–351]
Regulatory approval	Increasing support in regulations and organic standards [352]	Registration and commercialization can be lengthy and costly [298,353–355]
Production and storage	Can be mass-produced using fermentation technologies [356–359]	Shelf-life and formulation stability may be challenging [360–363]
Mode of action	Diverse mechanisms (competition, antibiosis, parasitism, induced resistance) [320,364]	Mechanisms not always fully understood; variable efficacy in the field [314,365–368]

3.5.2. Microbial Consortia and Synergistic Effects

Microbial consortia, involving the combination of different microbial species, have gained increasing attention as a strategy to enhance the effectiveness of biocontrol [295]. Recent studies indicated that multi-strain or multi-species formulations can provide broader-spectrum protection against plant pathogens while improving plant growth through synergistic plant–soil–microbe interactions [369]. For instance, the co-application of mycorrhizal fungi and rhizobacteria has been shown to promote plant vigor while simultaneously protecting against root pathogens [179,370,371]. Despite these benefits, developing and commercializing effective microbial consortia remains a challenge due to issues related to microbial compatibility, stability, and scalability. Ensuring that introduced microbes can establish and persist in the soil without being outcompeted by native microbial populations is a key concern that continues to be explored in ongoing research [372].

3.5.3. Organic Amendments and Soil Health in Disease Suppression

Organic amendments (OAs), such as composts, biochar, and green manures, represent another promising approach to microbiological disease control. These amendments contribute to soil health by enriching microbial diversity, enhancing nutrient cycling, and improving soil structure, which indirectly suppresses soil-borne pathogens [373]. Recent research highlights that organic amendments promote beneficial microbial communities that outcompete or inhibit plant pathogens, leading to long-term disease suppression. For example, fortified compost with *Trichoderma* sp. and biochar has been reported to enhance the abundance of disease-suppressive bacteria such as *Pseudomonas* and *Bacillus* spp. while simultaneously improving soil water retention, soil organic content, carbon sequestration, and soil microbial resilience [147,180,374]. Additionally, organic amendments can improve plant resilience against stressors by modulating rhizosphere microbiota and enhancing plant immune responses. Using water extracts derived from composts has also been shown to effectively suppress various soil-borne pathogens, suggesting that the suppressive effect is primarily biological, rather than chemical or physical [375].

However, one of the major limitations of organic amendment applications is their variable effectiveness, which is influenced by factors such as the soil type, the decomposition rate, and microbial community dynamics. In some cases, excessive organic matter inputs can lead to the proliferation of opportunistic pathogens or imbalances in soil microbial populations, potentially causing unintended negative effects on plant health [376]. The summarized aspects of OA application, including advantages and limitations, are presented in Table 6.

Table 6. Summarized aspects of organic amendments application.

Aspect	Advantages	Limitations
Soil health	Improves soil structure, fertility, and microbial activity [9,147,329,330,376–378]	Effects may vary, depending on soil type and amendment composition [147,329,330,379,380]
Microbial activity	Stimulates beneficial microbes that suppress pathogens [381–385]	May also induce heavy metal contamination and stimulate some pathogens if not properly managed [386–388]
Nutrient supply	Provides slow-release nutrients to plants [389–391]	Nutrient release is less predictable than synthetic fertilizers [392–394]
Disease suppression	Enhances natural suppressiveness (e.g., via microbial antagonists or competition) [373,395,396]	Inconsistent results, depending on quality, type, and application method [397,398]
Sustainability	Recycles organic waste; environmentally friendly [330,399,400]	Requires large quantities for field-scale use [394]
Residue-free	No harmful chemical residues on crops [401,402]	May take longer to see effects compared to synthetic treatments [379,396]
Compatibility with IPM	Suitable for organic farming and integrated pest management [403–405]	Not a stand-alone solution for severe disease outbreaks [382,397]
Cost	Low-cost and locally available materials can be used [147,380]	Transport, processing, and application can be labor-intensive and costly [379,394]
Pathogen inactivation	Composting can inactivate some soil-borne pathogens [406–409]	If not properly composted, may introduce new pathogens or weed seeds [410–414]

3.6. Challenges and Limitations of Microbiological Control

While microbiological control presents significant advantages over chemical methods, such as environmental safety, sustainability, and the potential for long-term disease suppression, it also faces considerable challenges. One of the primary drawbacks is the inconsistency in performance across different environmental conditions. Unlike chemical fungicides, which provide immediate and predictable effects, microbiological control often requires time to establish and may be influenced by biotic and abiotic interactions in the soil [415]. Furthermore, the regulatory approval process for microbial-based biocontrol agents remains complex and time-consuming, which can hinder their widespread adoption. Economic considerations, such as production costs, formulation stability, and application methods, also play a critical role in determining the feasibility of microbial-based approaches in large-scale agricultural systems [416,417].

3.7. Future Directions and Innovations

Despite these challenges, ongoing advances in microbial ecology, genomics, and biotechnology are continuously improving the effectiveness and applicability of microbiological control strategies. The integration of microbiome-based approaches with precision agriculture techniques, such as metagenomics and high-throughput sequencing, is providing valuable insights into how microbial communities interact with plant pathogens and how these interactions can be optimized for disease suppression [418]. Additionally, the use of bioinformatics tools and artificial intelligence in predicting microbial interactions and optimizing consortia formulations is opening new frontiers for the development of next-generation biocontrol strategies.

3.8. Conclusions

The microbiological control of plant pathogens offers a promising and environmentally friendly alternative to conventional disease management strategies. While microbial inoculants, organic amendments, and microbial consortia have demonstrated potential in controlling plant diseases, their effectiveness is influenced by a complex interplay of environmental, biological, and technical factors. Addressing the challenges associated with microbial-based disease control requires continued interdisciplinary research, technological advancements, and supportive regulatory frameworks to facilitate the transition toward sustainable and resilient agricultural systems.

4. Environmental Modification Techniques

This approach involves altering a plant physical and chemical environment to suppress or eliminate pathogens [419]. These strategies are often integrated with other management practices and aim to create unfavorable conditions for pathogen survival and development [36]. Adjusting factors such as pH, moisture, air circulation, and humidity can reduce plant disease incidence and severity without relying heavily on chemical treatments [11].

4.1. Soil Moisture Management

Soil moisture plays an important role in the development and spread of many soilborne and foliar pathogens [420]. Excessive moisture can create conditions favourable to the growth of Oomycetes like *Phytophthora* and *Pythium* spp., which thrive in moist conditions, and poorly drained soils [421]. Managing soil moisture through proper irrigation practices, soil structure, and drainage system improvements can significantly reduce pathogen pressure [36]. Recent studies highlight the importance of drip and precision irrigation systems in reducing disease incidence; for example, drip irrigation reduced the spread of *Phytophthora* root rot in citrus orchards by keeping the soil surface drier which limited the pathogen's ability to infect new roots [422,423]. Similarly, optimizing irrigation frequency and timing reduced the incidence of *Fusarium* wilt in greenhouse tomatoes by avoiding prolonged periods of soil saturation [424]. Improving soil structure through practices such as organic matter amendments and cover cropping can improve water infiltration and drainage, reducing the likelihood of waterlooging that promotes pathogen growth [425]. Cover crops like rye and clover improved soil porosity and reduced the incidence of *Verticillium* wilt in strawberries by preventing waterlogging and promoting a healthier soil environment [426].

4.2. Soil pH Adjustment

Soil pH influences the availability of nutrients and the activity of both pathogens and beneficial microbes [427]. Certain plant pathogens, such as *Plasmodiophora brassicae* (causal agent of clubroot disease in crucifers) and *Pythium* spp., thrive under acidic conditions [428]. Diseases like potato scab caused by *S. scabies* are more prevalent in alkaline soils. Adjusting soil pH to unfavorable levels for specific pathogens can be an effective disease management strategy [429]. Liming acidic soil to raise pH has been widely used to control clubroot disease in brassicas. Recent research by Geoffrey [430] found that applying lime to maintain a soil pH of 7.2 significantly reduced clubroot incidence in cabbage fields. Lowering soil pH using acidifying amendments like elemental sulfur or ammonium-based fertilizers can help control alkaline-soil pathogens [431]. Qi et al. [432] demonstrated that lowering soil pH below 5 reduced the severity of potato scab by limiting the growth of *S. scabies*. pH manipulation, integrating soil pH management with other practices, such as crop rotation and soil testing, can provide more sustainable and effective disease control [429].

4.3. Air Circulation and Humidity Control

Air circulation and humidity are critical factors in controlling foliar diseases, especially those caused by fungal pathogens such as *B. cinerea* (gray mold), *Alternaria* spp., and powdery mildew fungi [433]. High humidity and poor air circulation create a microclimate that promotes spore germination, infection, and the rapid spread of these pathogens [434]. Air circulation within plant canopies can be improved through pruning, appropriate plant spacing, and thinning [435]. For example, thinning apple trees and pruning lower branches improved airflow and reduced the incidence of apple scab (*Venturia inaequalis*) by 30% compared to unpruned controls [436]. Similarly, increased plant spacing in greenhouse cucumber production reduced the severity of downy mildew by lowering humidity levels within the canopy [437]. Humidity control in greenhouses and other enclosed environments is also essential for disease management. Techniques such as dehumidification, controlled irrigation, and ventilation can help maintain optimal humidity levels that discourage pathogen development [438]. For example, using dehumidifiers and controlled ventilation in a greenhouse reduced the incidence of *B. cinerea* in geraniums by 40% compared to conventional ventilation systems [439].

5. Integrated Environmentally Friendly Management

5.1. Combining Environmentally Friendly Techniques

Combining environmentally friendly techniques presents an appealing and sustainable solution, though it is not without inherent complexities and challenges [440,441]. Integrating various environmental methods for managing plant pathogens based on organic resource-mediated strategies like intercropping, crop rotation, and organic amendments enhances the resilience and sustainability of agroecosystems against plant pathogens [108]. Crop rotation interrupts the life cycles of soil-borne pathogens by incorporating a non-susceptible crop, leading to a decrease in pathogen populations. It helps in plant nutrition and the more effective management of plant diseases [442]. Intercropping improves plant diversity, inhibiting pathogen dissemination, and creating a more competitive environment for advantageous microbes [443]. Organic additives, such as compost and biochar, increase soil vitality and microbial diversity, thus providing unique benefits for long-term soil sustainability and contributing to improved disease resistance [444,445]. When combined, these methods encourage sustainable disease management by reducing dependence on chemical pesticides and fostering a balanced ecosystem that improves plant health and effectively manages plant pathogens.

Environmental management also enhances the success of genetic resistance and BCAs through synergistic mechanisms. In tomato cultivation, integrating tomato yellow leaf curl virus-resistant varieties with early planting and whitefly vector control measures yields far greater disease suppression than genetic resistance alone [396]. Soil health improvements through organic amendments further promote microbial diversity, enhancing the performance of biocontrol agents such as *Trichoderma* spp. against *R. solani* [446,447].

Nonetheless, several challenges impede the widespread adoption of integrated approaches. A major obstacle is the complexity of design and implementation. Effective integration requires extensive knowledge of pathogen biology, environmental interactions, and agronomic practices. For instance, while crop rotation is generally effective against soil-borne pathogens, it can inadvertently perpetuate diseases if alternative hosts are not properly excluded, as in the case of *Fusarium* spp. affecting both cotton and tomato [219]. Another challenge lies in the variability of environmental technique effectiveness, often dictated by climatic and edaphic conditions. Soil solarization, for example, requires sustained high temperatures to achieve adequate pathogen mortality, limiting its application in temperate regions [46]. Similarly, the success of biological control agents such as *B. subtilis* in suppressing bacterial diseases is influenced by soil moisture and temperature, leading to inconsistent field results [448]. The summarized aspects of the effectiveness of environmentally friendly techniques in controlling different types of plant pathogens are shown in Supplementary Table S1.

5.2. Integration with Chemical Control Methods

Combining environmental strategies with chemical control methods provides a comprehensive way to manage plant pathogens. Sustainable methods such as crop rotation, intercropping, and organic amendments can be integrated with the careful use of chemical fungicides or pesticides to lower pathogen pressure while decreasing chemical inputs. Moreover, genetic control techniques, like employing resistant plant varieties, enhance these strategies by offering natural disease resistance and minimizing the frequency of chemical applications [449,450]. This comprehensive strategy improves pathogen management while also fostering sustainable farming by protecting soil health, minimizing chemical resistance, and sustaining ecological equilibrium.

Moreover, integration plays a pivotal role in delaying the emergence of resistant pathogen strains. Chemical treatments applied in isolation, such as fungicides targeting *B. cinerea*, often select for resistant populations [451]. However, coupling environmental sanitation practices with chemical applications disrupts pathogen life cycles at multiple points. This strategy has proven effective, for example, against bacterial spot of tomato and pepper caused by *Xanthomonas* spp. [452]. Similarly, the use of reflective mulches and trap crops to limit aphid populations has significantly enhanced control of CMV, demonstrating how environmental interventions bolster chemical effectiveness [453]. Furthermore, when solarization is combined with minimal chemical applications, a synergistic effect often emerges, enabling effective disease suppression while reducing chemical residues in the environment [272].

Environmental methods may also be insufficient when facing viruses and phytoplasmas without complementary measures targeting insect vectors. For phytoplasma diseases like aster yellows, controlling the leafhopper vectors through habitat management must be supplemented with insecticide applications to achieve significant disease reduction [454]. Thus, while environmental interventions are critical, they often require integration with chemical or biological measures to be truly effective against complex pathogen systems. Economics poses a final significant barrier to integration. Integrated strategies generally demand higher upfront investment in knowledge acquisition, monitoring infrastructure, and sustainable inputs. This reality may discourage adoption by resource-limited farmers, who often prefer conventional pesticide-based systems for their immediate efficacy and lower initial costs [455].

Real-world applications further illustrate both the promise and limitations of integrated control. In viticulture, managing downy mildew (*Plasmopara viticola*) successfully combines resistant cultivars, canopy management for improved airflow, and minimal fungicide applications [456]. In rice, integrated management of bacterial blight (*Xanthomonas oryzae* pv. *oryzae*) emphasizes genetic resistance, field sanitation, and balanced fertilization, reserving bactericides for emergency intervention [457]. Similarly, controlling citrus Huanglongbing (‘*Candidatus* Liberibacter asiaticus’ integrates vector management, the rogueing of infected trees, and the deployment of tolerant rootstocks, highlighting the necessity of a multifaceted approach [458]. Ultimately, the integration of environmentally friendly and chemical disease management strategies represents a promising path towards sustainable agriculture. Future progress depends on advancing research into tailored, pathogen-specific protocols, supporting farmer education initiatives, and creating policies that encourage and subsidize integrated practices.

6. Quantitative and Comparative Contributions of Control Diseases Strategies

The review paper has presented a broad, qualitative evaluation of various environmentally friendly methods for plant pathogen control, across multiple pathosystems, providing some numerical data and comparative insights scattered across the sections and supporting a contextual and integrated use of the following key strategies:

(a) Host resistance and crop genetic diversity—top-tier effectiveness;
(b) Soil amendments, rotation, and organic inputs—medium to high (variable);
(c) Biological control—effective but climate-sensitive;
(d) Physical methods—useful for high-value crops or specific contexts;
(e) Integration of methods—highest overall performance.

Table 7 displays a synthesized summary based on the available data and references in the main text:

Table 7. Summarized aspects of comparative contributions of control diseases strategies.

Control Strategy	Documented Effectiveness	References/Notes
Use of resistant cultivars	Up to 100% protection in certain crops (e.g., virus-resistant cassava, mildew-resistant millet)	Demonstrated high effectiveness and cost-efficiency, especially in smallholder systems
Crop rotation	Reduces soil-borne pathogens significantly, though context-dependent	*Fusarium* in bananas needs >5 years fallow to reduce pressure
Intercropping	Improves plant diversity, enhances microbial competition, can significantly inhibit pathogen dissemination	Effective but highly variable; depends on crop and pathogen combination
Biofumigation	Suppression rates > 60%; Indian mustard can inhibit up to 80–100% of potato pathogens in vitro	Black mustard reduced *R. solani* by 75% for up to 6 months
Organic amendments	Improves suppressiveness, soil fertility, microbial diversity; effectiveness variable (25–75%)	Compost, biochar, manure, etc. influence microbial balance and resilience
Biological control agents (BCAs)	Variable; some BCAs reduce disease severity by 30–80% under favorable conditions	*B. subtilis*, *Trichoderma* spp., *Pseudomonas* spp. affected by humidity/soil temp

Table 7. *Cont.*

Control Strategy	Documented Effectiveness	References/Notes
Soil solarization/steaming	Up to 90–100% pathogen reduction if temperature maintained >45–50 °C for several days	Less effective in temperate climates without sustained heat
Hot water treatment (HWT)	Effective for seed/propagation material sterilization (e.g., eliminating *Clavibacter, Ralstonia* spp.)	Temperature/time must be optimized to avoid plant damage (e.g., 50 °C for 20–30 min)
Air circulation and humidity control	30–40% reduction in fungal disease incidence in greenhouse settings with proper ventilation	e.g., 40% drop in *Botrytis* incidence in geraniums
Soilless culture	Removes soil-borne pathogen pressure almost entirely, if managed correctly	High initial cost; widely used in high-value horticulture
Integrated techniques (IEPM)	Highest resilience and suppression across multiple pathogens (no exact %, but synergistic benefit emphasized)	Particularly effective when combining resistance, rotation, and BCA

Different control strategies' effectiveness can be quantitatively compared based on their ability to reduce disease incidence and severity as follows (Table 8). Physical techniques, biological control, and cultural and ecological management strategies are all effective methods for reducing plant diseases. However, their effectiveness can vary, depending on the specific crop, pathogen, and environmental conditions. Integrated disease management approaches, which combine multiple strategies, have been shown to be more effective than using a single strategy. By understanding the strengths and limitations of each method, farmers and agricultural practitioners can develop comprehensive disease management plans that optimize disease reduction while minimizing environmental impact.

Table 8. Effectiveness of control strategies in the reduction in plant diseases.

Strategy	Effectiveness (%)	References
Physical techniques (e.g., heat treatment)	39 (post-harvest control)–70	[459,460]
Biological control (e.g., *Trichoderma* spp.)	50–80	[461]
Pomegranate and carob extracts	77	[462]
Cultural and ecological management	30–60	[463]
Integrated eco-friendly components	75	[464]

7. Future Perspectives and Conclusions

Environmental techniques for managing plant pathogens represent a sustainable shift away from chemical-intensive agriculture, with strategies like soil solarization, hot water treatment, and steaming offering effective physical control. Cultural practices such as crop rotation, intercropping, and sanitation interrupt disease cycles and enhance agroecosystem resilience, while organic amendments—including compost, biochar, and green manures—improve soil health, promote beneficial microbes, and suppress pathogens through both direct and indirect mechanisms. Biological approaches, notably the application of antagonistic microorganisms, arbuscular mycorrhizal fungi, and plant growth-promoting rhizobacteria, have demonstrated multifaceted benefits in reducing pathogen loads and enhancing plant defense. Soilless cultivation techniques further contribute to plant health by minimizing soil-borne disease risks and improving environmental control in protected systems. Despite their proven potential, these techniques face limitations such as variability in effectiveness, challenges in standardization, and limited adoption due to labor or resource constraints. Looking ahead, emerging technologies like microbiome engineering and genome editing offer exciting possibilities to complement and amplify existing practices. Microbiome engineering can enable the design of tailored microbial consortia that improve disease suppression, nutrient cycling, and plant immunity—paving the way for precision biocontrol. Simultaneously, genetic modification and CRISPR-Cas technologies allow the development of crops with durable, multi-pathogen resistance traits that can be integrated with organic and microbial solutions for holistic plant protection.

To realize these advances, future research should focus on the following:

1. **Optimizing synergies among environmental techniques**—e.g., combining organic amendments with biocontrol agents or physical methods with crop diversification.
2. **Advancing microbiome**—based tools, supported by metagenomics and microbial ecology, to predict and manipulate soil suppressiveness.
3. **Enhancing regulatory and risk assessment frameworks**—for the use of engineered microbes and gene-edited crops in open-field conditions.
4. **Conducting long-term field trials** across diverse agroecological zones to validate the consistency and scalability of integrated strategies.
5. **Bridging ecological knowledge with data science**, enabling predictive modeling for disease outbreaks and microbiome responses to interventions.

In conclusion, the path to sustainable disease management lies in the integration of traditional ecological knowledge with cutting-edge biotechnological tools. A multidisciplinary and systems-based approach—uniting physical, biological, and cultural practices with innovations in genetic and microbial engineering—will be key to building resilient, productive, and environmentally responsible agricultural systems in the face of climate change and global food challenges.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy15071551/s1, Table S1: Results of the effectiveness of environmentally friendly techniques in controlling different types of plant pathogens.

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