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Disease Risks and Management in Greenhouse Medical Cannabis (*Cannabis sativa*) Production

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Abstract

Greenhouse cultivation is now widely used in medical cannabis (*Cannabis sativa*) production because it allows stable year-round harvests and more uniform product quality. At the same time, the structural features of controlled-environment systems enable high planting density, repeated cropping cycles, and large-scale clonal propagation. However, it also creates conditions that favor the growth, spread, and persistence of pathogens within the facility. This review summarizes the major disease challenges associated with greenhouse cannabis production and outlines management priorities that are critical for maintaining crop health and production stability. Persistent risks include systemic pathogens such as viroids, as well as foliar and floral fungal diseases, particularly powdery mildew and bud rot. Importantly, disease management is further constrained in medicinal cannabis production due to strict regulations on pesticide use and residue limits for medicinal products, which restrict the use of conventional chemical pesticides. Accordingly, this review focuses on integrated disease management approaches that combine pathogen-free propagation material, routine monitoring and diagnostics, environmental and canopy management, sanitation practices, and biologically compatible control tools. Prevention-based disease control and early detection throughout the production cycle are essential to reduce economic losses, maintain product quality, and support the long-term sustainability of the medical cannabis production system in greenhouse conditions.

Keywords: Medical Cannabis; Greenhouse Cultivation; Pathogens; Hop Latent Viroid; Powdery Mildew; Integrated Disease Management

Introduction

The global medical cannabis industry has rapidly transitioned toward controlled-environment agriculture, including greenhouse and indoor production systems, to ensure consistent cannabinoid profiles, pharmaceutical-grade quality, and year-round supply [1]. Unlike conventional field crops, medical cannabis cultivation depends heavily on vegetative propagation using cuttings derived from elite mother plants. While this system enables genetic uniformity, it simultaneously creates ideal conditions for the accumulation and rapid dissemination of systemic pathogens [1,2]. Unlike seed-based systems, infected mother plants can silently transmit viruses and viroids to thousands of progeny plants over repeated propagation cycles. Among these threats, Hop latent viroid (HLVd) has emerged as one of the most economically damaging pathogens in greenhouse-grown cannabis, causing latent infections associated with reduced biomass accumulation, decreased cannabinoid content, and impaired plant vigor [3,4]. In addition to systemic pathogens, high humidity, dense canopies, and restricted airflow, which are typical of greenhouse environments, favor the development of airborne fungal diseases [1,2]. Powdery mildew caused by *Golovinomyces* spp. remains the most frequently reported foliar disease in indoor cannabis facilities, while *Botrytis* cinerea causes devastating bud rot during flowering and post-harvest handling [5-7]. Root and crown diseases caused by soilborne pathogens such as *Fusarium* spp. and *Pythium* spp. further compromise plant establishment and productivity, particularly during propagation and early vegetative stages [5,8,9]. Despite the increasing economic importance of medical cannabis, standardized disease management frameworks tailored specifically for greenhouse production remain underdeveloped. Moreover, regulatory restrictions on pesticide registration and residue tolerance impose additional challenges for growers, emphasizing the importance of preventive management and integrated disease control strategies. This review aims to (1) summarize the major pathogens affecting greenhouse-grown medical cannabis, (2) analyze disease epidemiology and transmission pathways, (3) discuss current diagnostic and surveillance approaches, and (4) propose an integrated disease management framework adapted to the unique biological and regulatory constraints of the medical cannabis industry.

Fungal Diseases

Powdery Mildew (Golovinomyces spp.)

Powdery mildew (*Golovinomyces* spp.) is the most commonly reported foliar disease in greenhouse cannabis production [10,11] (Table 1). Infection is characterized by white powdery fungal growth on leaf surfaces, petioles, and stems, leading to reduced photosynthetic capacity, premature senescence, and compromised product quality [2]. Powdery mildew development is favored by moderate temperatures (18-26°C), low airflow, and high nighttime humidity [12]. Unlike many fungal pathogens, powdery mildew does not require free water on leaf surfaces for infection, allowing it to proliferate rapidly in controlled environments.

Epidemics of powdery mildew in greenhouse-grown medical cannabis are primarily initiated by residual inoculum persisting within production facilities or by the introduction of infected but asymptomatic plant material. *Golovinomyces* spp., the dominant powdery mildew pathogens of cannabis, produce abundant airborne conidia that readily disperse through ventilation systems and remain viable on greenhouse surfaces, tools, and plant debris, enabling rapid secondary spread under favorable environmental conditions [2]. Preventive management is, therefore, the most effective strategy for controlling powdery mildew in medical cannabis systems. Environmental manipulation plays a central role, including maintaining relative humidity below critical thresholds, improving horizontal air flow, reducing canopy density through pruning, and optimizing plant spacing to minimize microclimatic conditions that favor spore germination and colony establishment. Because clonal propagation can rapidly amplify infected source material, routine inspection of mother plants and cuttings, combined with strict sanitation protocols, is essential to prevent facility-wide outbreaks.

Chemical control options are limited by regulatory restrictions on pesticide residues in medicinal products. Consequently, sulfur-based products and potassium bicarbonate formulations are among the most widely adopted tools for powdery mildew suppression in commercial cannabis production. Sulfur acts primarily by inhibiting spore germination and mycelial growth, whereas bicarbonates disrupt fungal cell membrane integrity and alter surface pH, creating unfavorable conditions for pathogen development [5,13]. In addition, biological control agents such as *Bacillus subtilis*, *B. amyloliquefaciens*, and *Ampelomyces quisqualis* have been increasingly integrated into disease management programs due to their compatibility with organic and low-residue production systems [14,15].

Repeated application of a narrow range of fungicidal products can promote the selection of tolerant pathogen populations under continuous production of cannabis in the indoor cultivation system. Although comprehensive resistance monitoring data for *Golovinomyces* spp. populations in cannabis are still limited, resistance development has been widely documented in powdery mildew pathosystems of other greenhouse crops, underscoring the need for proactive resistance management strategies [16].

These challenges highlight the importance of integrated disease management frameworks that combine early detection, environmental optimization, sanitation, biological control, and strategic rotation of compatible disease suppression products. Such integrated approaches not only reduce epidemic risk but also align with the regulatory, safety, and sustainability requirements of the medical cannabis industry.

Botrytis Bud Rot (Botrytis cinerea)

Botrytis cinerea is the causal agent of bud rot, one of the most destructive diseases affecting greenhouse-grown medical cannabis, particularly during the flowering and post-harvest stages [1,2] (Table 1). Infection typically initiates in senescent floral tissues, damaged bracts, or wounded plant surfaces and progresses rapidly under high humidity conditions. Visible symptoms include gray mold sporulation, water-soaked lesions, tissue necrosis, and eventual collapse of floral structures, resulting in substantial yield reduction and severe deterioration of product quality [2,17]. Because harvested inflorescences represent the primary marketable product in medical cannabis production, even low disease incidence can lead to disproportionate economic losses.

Table 1: Major pathogens affecting greenhouse-grown medical cannabis (*Cannabis sativa*) and their epidemiological characteristics.

Pathogen Type	Causal organism	Disease	Symptoms	Favorable conditions	Transmission route	Management
Fungi	*Golovinomyces* spp.	Powdery mildew	White powdery lesions on leaves and stems, reduced photosynthesis	Moderate temperature (18-26°C), low airflow, high night humidity	Airborne conidia, contaminated plant material	Preventive sprays, air circulation improvement, resistant cultivars
	Botrytis cinerea	Bud rot (gray mold)	Necrotic flowers, gray sporulation, tissue collapse	High humidity (>80%), dense canopy, condensation	Airborne conidia, senescent tissues	Canopy thinning, humidity control, sanitation

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	Fusarium spp.	Root rot, Wilt	Root browning, vascular discoloration, plant wilting	Warm substrate temperature, poor drainage	Contaminated substrate, irrigation water	Substrate sterilization, biological control, sanitation
Oomycetes	*Pythium* spp.	Root rot, Damping-off	Root necrosis, stunted growth, damping-off	High moisture, recirculating hydroponic systems	Waterborne zoospores	Water sanitation, root zone temperature control
	Hop latent viroid (HLVd)	Latent systemic disease	Reduced vigor, shortened internodes, decreased cannabinoid content	Clonal propagation systems	Mechanical transmission, cuttings	Molecular diagnostics, clean stock programs

The unique floral morphology of cannabis inflorescences strongly contributes to *Botrytis* susceptibility. Dense flower clusters and compact bud architecture create localized microenvironments characterized by reduced airflow and elevated moisture retention, which favor fungal colonization and sporulation [1,18]. Condensation on flower surfaces, particularly during nighttime temperature fluctuations, further increases infection risk. In greenhouse systems, inadequate ventilation and poor horizontal air movement exacerbate these microclimatic conditions, facilitating rapid epidemic development.

A major challenge associated with *Botrytis* bud rot is its latent infection behavior. *B. cinerea* can establish quiescent infections during early flowering stages and remain asymptomatic until favorable environmental conditions trigger aggressive colonization later in the production cycle [19]. This latent phase complicates early disease detection and allows infected plant material to enter harvest and post-harvest handling processes, where secondary spread can occur through airborne conidia and contaminated surfaces. Consequently, *Botrytis* outbreaks often intensify during drying and storage stages if environmental conditions are not carefully controlled.

Effective management of *Botrytis* bud rot in medical cannabis production relies primarily on preventive and cultural strategies, due to the restrictions on pesticide residues in medicinal products. Canopy management practices, including selective defoliation, flower spacing optimization, and removal of senescent tissues, reduce humidity retention within the canopy and limit infection sites [20]. Environmental control is equally critical, with emphasis on maintaining relative humidity below critical thresholds, stabilizing temperature gradients, and improving air circulation to suppress sporulation and disease progression. Sanitation of production areas, harvest equipment, and drying rooms further reduces residual inoculum and limits secondary contamination.

Due to the regulatory limitations on pesticide residues in medical cannabis products, biological control agents have gained increasing importance in *Botrytis* management programs. Antagonistic microorganisms such as *Trichoderma* spp. and *Bacillus* spp. have demonstrated efficacy in suppressing *B. cinerea* through competition, antibiosis, and induction of plant defense responses [21,22].

Continuous greenhouse production and repeated use of limited disease suppression tools may increase the risk of reduced sensitivity or tolerance development in *Botrytis* populations. Resistance to multiple fungicide classes has been widely documented in *B. cinerea* populations from other greenhouse crops, highlighting the importance of resistance-aware management strategies even when chemical options are limited [23]. Rotating compatible biological and low-risk products, combined with strict cultural and sanitation practices, can help mitigate this risk.

Overall, *Botrytis* bud rot represents a persistent threat to greenhouse medical cannabis production due to its strong association with floral tissues, latent infection behavior, and post-harvest transmission potential. Integrated disease management approaches that combine environmental optimization, canopy management, sanitation, and biological control are therefore essential to minimize epidemic development and protect both yield and product quality.

Damping-off, Root Rot and Wilting Diseases (Fusarium spp. and Pythium spp.)

Soilborne pathogens belonging to the genera *Fusarium* and *Pythium* are among the most important causal agents of damping-off, root rot, and vascular wilt diseases in greenhouse-grown medical cannabis [1,2] (Table 1). These diseases are particularly problematic during the propagation and early vegetative growth stages, when root systems are still developing and plants exhibit limited physiological resistance to pathogen invasion. Infection commonly results in root browning, reduced root biomass, vascular discoloration, leaf chlorosis, wilting, stunted growth, and eventual plant collapse under severe disease pressure [24].

Damping-off caused by *Pythium* species is frequently observed in newly rooted cuttings and seedlings, where zoospore-mediated infection rapidly destroys root tissues under saturated or poorly drained substrate conditions [25]. In contrast, *Fusarium* spp. often cause chronic root rot and vascular wilt by colonizing root tissues and invading the xylem, leading to impaired water transport and progressive wilting symptoms [26]. Because both pathogens can persist in substrates and irrigation systems, repeated crop cycles in greenhouse production facilities promote pathogen accumulation and long-term disease pressure.

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Introduction of *Fusarium* and *Pythium* into cannabis production systems commonly occurs through contaminated growing media, untreated irrigation water, reused containers, and infected propagation material [25]. Hydroponic and recirculating irrigation systems further increase disease risk by enabling rapid dissemination of motile *Pythium* zoospores and fungal propagules throughout production units [27]. Warm root-zone temperatures, excessive moisture, and low oxygen availability in substrates exacerbate disease severity by creating conditions favorable for pathogen proliferation and host susceptibility.

Effective management of root and crown diseases in greenhouse medical cannabis relies primarily on preventive and cultural practices. Substrate sterilization or the use of pathogen-free commercial growing media reduces initial inoculum levels [1]. Water sanitation technologies, including filtration, ultraviolet treatment, and chemical disinfection, are critical for minimizing pathogen movement in recirculating irrigation systems [27]. Root-zone temperature management and optimization of irrigation scheduling further limit disease development by reducing stress on plants and suppressing pathogen activity.

Beneficial microorganisms such as *Trichoderma* spp. and *Bacillus* spp. suppress soilborne pathogens through multiple mechanisms, including competition for nutrients and space, production of antifungal metabolites, and induction of plant defense responses [21,22].

Continuous production cycles and repeated reuse of cultivation infrastructure can increase the persistence of soilborne pathogen populations. Therefore, integrated disease management strategies that combine sanitation, environmental control, biological suppression, and routine monitoring are essential for minimizing losses caused by *Fusarium* and *Pythium* in greenhouse medical cannabis systems.

Bacterial Diseases

Compared with fungal and viroid-associated problems, bacterial diseases in cannabis appear to be less frequently documented in the peer-reviewed literature, and their incidence may be underestimated due to sporadic reporting and diagnostic limitations in commercial settings. Reported bacterial disease include blight/leaf spot symptoms associated with *Pseudomonas* spp. and *Xanthomonas* spp., and crown gall caused by *Agrobacterium* spp., typically favored by wounding, high humidity, and poor sanitation [1,2,28]. Because bacterial pathogens can spread rapidly via splashing water, recirculating irrigation, contaminated tools, and handling practices, hygiene protocols and environmental management remain the primary control measures. Further research is needed to clarify the epidemiology and economic impact of bacterial diseases in medical cannabis production.

Viral and Viroid Diseases

Hop Latent Viroid (HLVd)

Hop latent viroid (HLVd), originally described in hop (Humulus lupulus), is now recognized as a major systemic threat in clonal cannabis production systems, with increasing reports of detection and measurable yield and quality penalties in greenhouse operations [4,29,30] (Table 2). Unlike many fungal and bacterial pathogens, HLVd establishes persistent systemic infections that directly affect plant physiology and productivity. Infected cannabis plants often exhibit subtle or no visible symptoms, particularly during early growth, making symptom-based diagnosis unreliable and enabling silent spread through vegetative propagation [30]. Nevertheless, quantitative assessments have demonstrated substantial reductions in biomass accumulation, shortened internode length, decreased trichome density, and significant declines in cannabinoid concentration, including tetrahydrocannabinol and cannabidiol content [4,29,30]. These yield and quality losses translate into considerable economic damage, particularly in high-value medical cannabis production systems.

Table 2: Recommended Hop latent viroid (HLVd) monitoring and clean stock management protocol for greenhouse medical cannabis.

Production stage	Sampling target	Diagnostic method	Recommended frequency	Management action
Mother plant	Young leaves, petioles	RT-qPCR	Monthly	Immediate removal, destruction, sanitation of surrounding area
Propagation	Incoming cuttings	RT-qPCR	Every batch	Reject contaminated lots
Vegetative growth	Random plant sampling	RT-qPCR	Every 4–6 weeks	Isolate and remove infected plants
Flowering stage	Symptomatic plants	RT-qPCR	As needed	Prevent further propagation
Facility sanitation	Tools, surfaces	Surface swab PCR	Quarterly	Improve sanitation protocols

Transmission of HLVd occurs predominantly through mechanical means. Contaminated pruning tools, worker handling, shared equipment, and repeated vegetative propagation of infected mother plants represent the primary dissemination routes [4,30]. Because medical cannabis production relies heavily on clonal propagation, HLVd can rapidly spread throughout entire facilities

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once introduced. In contrast to insect-transmitted plant viruses, HLVd spreads efficiently within closed greenhouse systems through routine horticultural practices, making biosecurity and sanitation critical control points.

Molecular diagnostic tools have become indispensable for HLVd management. Reverse transcription quantitative polymerase chain reaction (RT-qPCR) is currently regarded as the standard method for sensitive and reliable detection of HLVd in cannabis tissues [3]. Regular screening of mother plants, propagation material, and incoming plant stock is essential for early detection and outbreak prevention (Table 2). Because no curative treatments are currently available for viroid infections, immediate removal and destruction of infected plants remain the only effective mitigation strategy once HLVd is detected.

Implementation of clean stock programs has therefore become a central component of disease management in greenhouse cannabis systems. Such programs emphasize pathogen-free propagation material, routine molecular surveillance, tool disinfection, and strict separation of production zones. These preventive measures represent the most effective approach for limiting HLVd establishment and long-term persistence in controlled-environment production systems.

Other Viruses and Emerging Pathogens

In addition to HLVd, several plant viruses have been reported in cannabis production systems, although their economic impact currently appears lower than that of HLVd infections. Lettuce chlorosis virus has been associated with cannabis plants showing chlorosis and growth abnormalities, indicating the potential for cross-crop pathogen pressure in shared protected-cultivation regions [31]. In addition, recent virome and genomic studies continue to report novel or emerging viral agents from hemp/cannabis-associated hosts, underscoring the need for ongoing surveillance [32,33]. Advances in high-throughput sequencing technologies have significantly expanded the known virome of cannabis. Metagenomic surveys have revealed the presence of previously uncharacterized viral agents and latent infections that may remain undetected using conventional diagnostic approaches [3,33]. These discoveries highlight the importance of continuous pathogen surveillance, particularly as global germplasm exchange and international movement of plant material increase.

Although many currently identified viruses appear to cause limited direct damage, their potential interactions with other pathogens, environmental stress factors, and host physiology remain poorly understood. Mixed infections involving viroids, viruses, and fungal pathogens may exacerbate disease severity and contribute to unpredictable production outcomes. Further research is therefore required to clarify virus epidemiology, transmission pathways, and long-term impacts on medical cannabis productivity and quality.

Diagnostic Strategies and Pathogen Surveillance

Visual Scouting and Symptom-Based Monitoring

Routine visual scouting remains a fundamental component of disease management in greenhouse medical cannabis production. Regular inspection of foliage, stems, roots, and inflorescences enables early detection of diseases such as powdery mildew, *Botrytis* bud rot, and root rot, allowing timely intervention before epidemic escalation [1,2]. Symptom-based monitoring is particularly effective for foliar fungal diseases, where visible signs such as powdery lesions, necrotic tissues, and mold sporulation provide early warning indicators of disease development.

However, reliance on visual diagnosis alone is insufficient for detecting systemic pathogens. Viroid infections such as HLVd frequently remain latent or express only subtle symptoms during early growth stages, resulting in undetected pathogen dissemination through vegetative propagation [4,29]. Similarly, root pathogens can establish infections before aboveground symptoms become apparent. Therefore, visual scouting should be integrated with laboratory-based diagnostic tools to improve detection accuracy and surveillance reliability.

Molecular Diagnostics

Molecular diagnostic technologies have become indispensable for pathogen detection in medical cannabis production systems. Polymerase chain reaction (PCR) and reverse transcription quantitative PCR (RT-qPCR) provide sensitive and specific detection of viral/viroid nucleic acids and are increasingly integrated into routine surveillance workflows for cannabis production [3]. These tools enable early identification of infected plants before symptom expression, facilitating rapid containment and removal.

RT-qPCR is currently regarded as the standard for detection of HLVd and other systemic pathogens in cannabis [4,29]. Routine screening of mother plants, propagation material, and incoming plant stock using molecular assays significantly reduces the risk of large-scale outbreaks (Table 2). To reduce testing costs while maintaining coverage, pooled-sample screening can be adopted in commercial operations [34]. The integration of molecular diagnostics into routine production workflows represents a critical step toward proactive disease management and biosecurity in greenhouse cannabis systems.

Clean Stock Programs

Establishing pathogen-free propagation material is a cornerstone of disease prevention in medical cannabis production. Clean stock programs integrate routine molecular testing, controlled propagation environments, and strict sanitation/biosecurity protocols to prevent pathogen entry and facility-wide spread (Table 2). Key components of clean stock programs include regular RT-qPCR screening for viroids and viruses, isolation of

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high-risk production zones, disinfection of tools and work surfaces, and controlled movement of personnel between cultivation areas. By ensuring that only verified pathogen-free cuttings enter the production pipeline, clean stock programs serve as the foundation for sustainable and scalable greenhouse cannabis production.

Integrated Disease Management

Integrated disease management (IDM) is essential for sustainable greenhouse medical cannabis production due to continuous cropping cycles, clonal propagation systems, and regulatory limitations on chemical disease control tools. Effective IDM programs integrate preventive cultural practices, sanitation, environmental control, biological suppression, and targeted use of compatible disease control products to minimize pathogen pressure across all production stages.

Mother Plant Stage

Mother plants represent the most critical control point in greenhouse cannabis production because they serve as the primary source of vegetative propagation material (Table 3). Systemic pathogens such as HLVd can persist asymptomatically in mother plants and be transmitted to large numbers of progeny through repeated cutting cycles. Strict sanitation protocols must be implemented at this stage. Dedicated pruning tools, gloves, and working surfaces should be assigned exclusively to mother plant areas to minimize cross-contamination between production zones. Tool disinfection using appropriate sterilants between plants further reduces mechanical transmission risks. Restricted access policies and controlled worker movement between cultivation areas enhance biosecurity and reduce pathogen introduction. Establishing physically separated mother plant rooms with independent environmental control systems can further reduce disease pressure and facilitate targeted monitoring programs. These measures collectively form the foundation of clean stock maintenance in greenhouse medical cannabis systems.

Propagation Stage

Propagation represents one of the most vulnerable stages in cannabis production due to the physiological stress experienced by cuttings and the high humidity conditions required for rooting. Elevated moisture levels create favorable environments for damping-off pathogens and opportunistic fungal infections. Optimization of humidity, temperature, and airflow reduces pathogen establishment while maintaining suitable conditions for root development (Table 3). Use of sterilized or pathogen-free substrates minimizes initial inoculum loads and reduces disease introduction risks. Biological control agents such as *Trichoderma* spp. and *Bacillus* spp. can be incorporated into propagation substrates or delivered through irrigation programs to suppress soilborne pathogen populations and improve root health. Incoming plant material should undergo quarantine and molecular diagnostic screening prior to integration into production systems to prevent pathogen introduction.

Table 3: Stage-specific integrated disease management (IDM) framework for greenhouse-grown medical cannabis.

Growth stage	Primary disease risk	Preventive strategies	Monitoring tools	Control measures
Mother plant	HLVd, powdery mildew	Dedicated tools, restricted access, clean stock maintenance	RT-qPCR, visual scouting	Removal of infected plants, sanitation
Propagation	Root rot, damping-off	Sterilized substrate, humidity control	Root inspection, microbial monitoring	Biological control agents, water sanitation
Vegetative growth	Powdery mildew	Airflow optimization, canopy management	Weekly scouting	Preventive fungicide rotation
Flowering	Botrytis bud rot	Humidity control, flower spacing	Environmental sensors, scouting	Targeted fungicide/biocontrol applications
Harvest/ Post-harvest	Postharvest mold	Clean drying rooms, airflow control	Spore monitoring	Sanitation, environmental control

Vegetative Growth Stage

During vegetative growth, rapid canopy expansion increases humidity retention and reduces airflow within plant stands, thereby increasing the risk of foliar disease development. Canopy management practices, including pruning and optimized plant spacing, improve air circulation and reduce microclimatic conditions favorable for pathogen growth [1,2]. Routine disease monitoring through visual scouting and targeted molecular testing supports early detection and rapid intervention. Preventive applications of approved fungicides and biological control products may be implemented as part of resistance management strategies where permitted by regulatory frameworks (Table 3). Rotation of compatible disease suppression products is recommended to minimize the risk of tolerance development in pathogen populations [23]. Maintaining stable environmental conditions and minimizing abiotic stress further enhances plant resistance and contributes to overall disease suppression.

Flowering Stage

The flowering stage represents the highest risk period for *Botrytis* bud rot and other floral diseases due to dense inflorescence structures and increased humidity within the canopy [1,2]. Effective management during this stage requires

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strict environmental control, including maintenance of optimal humidity levels, improved air circulation, and stabilization of temperature gradients to prevent condensation on floral tissues. Canopy thinning and removal of senescent tissues reduce infection sites and limit moisture accumulation within flower clusters. Targeted preventive treatments should be applied based on disease risk assessments, environmental monitoring data, and historical disease pressure within production facilities (Table 3). Early intervention during flowering is critical to protect product quality and prevent post-harvest contamination.

Harvest and Post-Harvest Handling

Post-harvest environments can serve as major reservoirs for fungal spores and secondary contamination sources. Drying rooms with inadequate airflow and elevated humidity frequently promote mold development on harvested inflorescences, leading to product rejection and regulatory non-compliance [2]. Effective post-harvest disease management requires sanitation of drying rooms and equipment, controlled humidity management, and proper spacing of plant material to ensure adequate airflow (Table 3). Environmental monitoring systems should be used to maintain stable drying conditions that suppress fungal growth while preserving product quality. Standardized post-harvest handling protocols further reduce contamination risk and support consistent production of pharmaceutical-grade cannabis products.

Conclusion

Greenhouse medical cannabis production combines high plant density, continuous cropping, and clonal propagation, creating a production ecology where pathogens can persist and spread rapidly. This review highlights that the most consequential disease risks arise from systemic infections (especially HLVd) and humidity-driven fungal diseases (powdery mildew and *Botrytis* bud rot), with additional losses linked to soilborne root and crown pathogens such as *Fusarium* and *Pythium*. Because pesticide options and residue tolerances are tightly constrained in medicinal markets, disease control must be built around prevention rather than cure.

A practical management priority is to treat the production pipeline as a series of biosecurity "control points." Mother plants and propagation systems are the most decisive leverage points for preventing facility-wide spread, particularly for latent systemic pathogens. Routine RT-qPCR screening, strict tool and personnel hygiene, and clean stock programs provide the most reliable means of reducing inoculum entry and amplification. Across vegetative growth and flowering, environmental control and canopy architecture (airflow, humidity management, spacing, and removal of senescent tissues) remain central for limiting powdery mildew and *Botrytis* epidemics. Finally, harvest and post-harvest sanitation and drying-room climate control are essential to prevent late-stage disease expression and product contamination.

Overall, sustainable greenhouse cannabis production will depend on integrated disease management systems that combine early detection, clean propagation material, environmental optimization, sanitation, and compatible biological tools. Standardized surveillance and stage-specific IDM protocols supported by industry-wide reporting and continued research on pathogen epidemiology, mixed infections, and control efficacy will be critical to protect yield, maintain cannabinoid quality, and ensure long-term production stability under controlled-environment cultivation.

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