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RESEARCH ARTICLE

EMERGING DISEASES IN GINGER CULTIVATION: CHALLENGES, DETECTION, AND CONTROL

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ABSTRACT

Zingiber officinale, commonly known as ginger, is a valuable crop in Malaysia, recognized for its economic contributions, culinary significance, and medicinal properties. However, recent declines in ginger production, despite high market demand in Malaysia, gingers are largely attributed to diseases caused by numerous pathogens, primarily bacteria, fungi, and viruses. Diseases in ginger, including bacterial wilt, rhizome rot, leaf spot, and mosaic disease, pose significant challenges by reducing both the yield and quality of ginger, negatively impacting local farmers and the agricultural sector in Malaysia. While diseases such as bacterial wilt and rhizome rot exhibit overlapping symptoms, advancements in technology have facilitated diverse diagnostic approaches for their detection, allowing for accurate and rapid diagnoses. For instance, diagnostic methods such as RT-PCR, ELISA, LAMP, and machine learning algorithms are widely used for diagnostic purposes. Moreover, various control approaches have been introduced to manage disease infections including the application of fungicides, bactericides, seed and soil management, as well as physical and biological practices. This article addresses the recent issues concerning emerging diseases in ginger, highlighting advancements in diagnostic instruments and strategies for controlling the spread of these diseases in Malaysia.

KEYWORDS

Zingiber officinale, ginger, bacterial wilt, rhizome rot, leaf spot, mosaic disease, diagnostic techniques, disease control

1. INTRODUCTION

Ginger, scientifically known as *Zingiber officinale* is a flowering plant belonging to the family Zingiberaceae. The members of this family are recognized for their rhizomes, which are widely utilized in herbal medicine, food seasoning, and cosmetic products (Mao et al., 2019). In Southern Asia and India, ginger is often employed as an herb, valued for the aroma produced by its ketones, as well as its role as a flavoring agent in culinary applications (Bode and Dong, 2011). In medicine, the rhizome is primarily used due to its richness in therapeutic agents, which are beneficial for pharmacological and physiological functions. It helps maintain the normal operation of the body without reliance on synthetic drugs. Ginger exhibits properties such as antioxidant, anti-inflammatory, and anti-nausea effects, as it is composed of bioactive components (Bode and Dong, 2011; Deng et al., 2022; Ibrahim et al., 2007).

Ginger does not grow in the wild and relies on cultivation. It thrives in warm, humid climates with adequate rainfall yearly, at altitudes of up to 1,500 meters above sea level (Yaseer Suhaimi et al., 2012). Major ginger-producing regions include, Nigeria, and several Asia countries such as Nepal, China, Indonesia, and Malaysia. The optimal growth temperature for ginger ranges from 25ºC to 30ºC, which these countries experience during extended warm seasons. Temperature below 12ºC can damage ginger plants (Zhang et al., 2022). High humidity is also critical for the growth of ginger, as it helps to maintain soil moisture and reduces water loss caused by transpiration during the plant's growth phases.

In Malaysia, ginger is cultivated commercially in areas such as Bentong (Pahang), Banting (Selangor), Pontian (Johor), Keningau and Tambunan (Sabah), and Bakun (Sarawak) (David et al., 2018; Yaseer Suhaimi et al., 2012). Approximately 16% to 20% of the 320 species in the Zingiberaceae family are edible in Peninsular Malaysia (Ibrahim et al., 2007). Despite the diversity of ginger species in Peninsular Malaysia, Sabah remains Malaysia's leading producer, particularly in Tambunan, which is known for the Sabah Cultivar Ginger. This species is typically cultivated between March and April (Cosmas et al., 2016). Due to advancements in the biotechnology sector in Sabah, this species has seen in increasing market demand, benefiting local farmers and contributing significantly to the agricultural economy.

However, despite its potential, ginger cultivation has experienced significant declines due to diseases that severely impact production, reducing both yield and quality. In Malaysia, particularly in Sabah, ginger production has faced significant challenges, previously declining due to disease outbreaks such as bacterial wilt, which severely affected crops in 2005 (Cosmas et al., 2016). Consequently, ginger production decreased from 467 hectares in 2006 to 197 hectares in 2016 because of these diseases. This decline has led to increased reliance on imported ginger, resulting in low demand for locally produced ginger. Furthermore, this has resulted in economic losses, as highlighted by some researchers indicating that ginger sales decreased in 2005-2006 due to the bacterial wilt outbreak (Wubshet, 2018).

Diseases in ginger, such as bacterial wilt, rhizome rot, leaf spot, and mosaic disease, pose challenges to the agricultural economy in Malaysia. The emergence of these diseases in ginger cultivation concerning as they not

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only lead to significant reductions in yield and quality, but also negatively impact the economy of ginger farming (Wubshet, 2018). Therefore, to prevent disease outbreaks, advancements in diagnostic technologies have facilitated better monitoring of the causes and symptoms of these diseases. Techniques such as RT-PCR, ELISA, LAMP, and machine learning have enhanced more understanding of the disease and its management strategies (Zhang et al., 2022). Through research and study, effective control mechanisms can be developed, offering solutions to reduce and eliminate diseases in ginger cultivation.

2. Diseases in Ginger

2.1 Bacterial Wilt

Bacterial wilt is an emerging plant disease caused by *Ralstonia solanacearum*, a gram-negative bacterium that can lead to severe economic losses in agricultural crops. The disease originated in Southeast Asia and India, where ginger has been cultivated for years. The bacterium was identified in the 19th century as the causative agent of bacterial wilt, and its role in ginger wilt was confirmed in the 20th century. One of the earliest cases of bacterial wilt in ginger was reported in India in 1941 by Thomas from the Malabar region. Recent cases of bacterial wilt have been reported in the Junin region of Peru (March 2024), Heho township in Myanmar (2021), and the Bench-Sheko Zone of Ethiopia (2019) (Soto-Heredia et al., 2024; Aysanew and Alemayehu, 2022). These recent cases were caused by *R. solanacearum*. In Ethiopia, ginger is an important spice, but reports indicate that the disease is widely spread, with incidence rates ranging from 91.6% to 98.9%, causing total yield loss of ginger and impacting economic growth (Aysanew and Alemayehu, 2022; Benti, 2023).

This disease primarily affects the vascular tissue, as the bacterium predominantly infects the xylem, which is abundant in nutrients and moisture and facilitates rapid movements throughout the plant. This bacterium necessitates plant as hosts and is capable of infecting over 200 species, including ginger, by targeting its vascular system. *R. solanacearum* thrives in warm, moist conditions, with an optimal temperature range of 28-30ºC, which aligns with the ideal growing conditions for ginger (15-38ºC) (Shi et al., 2023). This creates a suitable environment for bacterial infection.

R. solanacearum enters the internal parts of the ginger plant through openings such as stomata on leaf surfaces, natural openings in root hairs, or wounds created by pests or environmental damage (Behera et al., 2020). Symptoms of infection by this bacterium are distinct in ginger plants. One prominent symptom is wilting, which begins with leaf drooping during the day, starting at the tips. Other symptoms include yellowing at the lower part of leaf, leading to severe necrosis of the plant. At the base part of the plant, the symptoms manifest as the development of water-soaked and brown rhizomes that emit a foul smell (Behera et al., 2020). Stems and rhizomes may exude a white ooze, due to bacterial activity.

As this bacterium mainly infects xylem, it invades xylem vessels, blocking water flow from the roots to the leaves (Lowe-Power et al., 2018; Shi et al., 2023). Cross-sections of the vascular tissue reveal browning and bacterial ooze may flow out from cuts. The bacteria can be transferred to young plants from infected tubers, leading to the rapid collapse of these young plants. The leaves may remain green after infection until the moisture inside of the leaves is completely depleted.

2.2 Rhizome Rot in Ginger

Rhizome rot in ginger is a severe disease that affects ginger production and quality, reducing yields by 50-90% (Yadav et al., 2023). The disease is caused by soil-borne pathogens, including bacterial species and primarily fungal species such as *Phythium* spp., *Rhizoctonia solani*, and *Fusarium* spp. This disease has greatly affected Brazil as these pathogens infect the rhizomes of ginger in the field, packing houses, storage, and refrigerated containers, resulting in significant losses for ginger industry in Brazil (Moreiral et al., 2013). The main fungal species responsible for this disease is *Fusarium oxysporum*, which is implicated in many cases of rhizome rot worldwide. The first case of rhizome rot caused by this fungal species was reported in Gujarat, India, in 1907 (Meenu and Kaushal, 2017). Subsequent cases of rhizome rot caused by the same fungal species have been reported in Hawaii, Brazil, Australia, and China.

Phythium spp. and *Fusarium oxysporum* can be transmitted to ginger plants through several pathways. These fungi primarily reside in soil, and have long survival traits that allow them to remain dormant for years, infecting the rhizomes when conditions are favorable (Tilahun et al., 2022). They can also be transmitted through infected planting material and equipment that are not properly treated before planting, allowing the spread of the fungus from one plant to another (Tilahun et al., 2022; Yadav et al., 2023). Additionally, *Fusarium oxysporum* can be transmitted through water when irrigation systems or rainfall come into contact with infected soil, carrying the fungus to healthy plants, especially in fields with poor drainage where waterlogging often occurs (Matthews et al., 2023).

The rhizome rot caused by these fungal species shows distinct symptoms in both the upper and lower parts of the ginger plant, typically affecting the plant during its growing period (Tilahun et al., 2022). Parts of the ginger plant, such as sprouts, developing roots, and rhizomes, are highly susceptible to infection. Infected plants will exhibit yellowing of leaves that progresses upward as the infection spreads (Matthews et al., 2023). As the disease progresses, the leaves begin to wilt as the fungus blocks the xylem, the main channel for water transport. The plant also experiences stunted growth (dwarfing), resulting in reduced height and smaller size (Yadav et al., 2023). The leaves will show necrosis primarily at the tips and edges, turning brown or black. Branches of the ginger plant may collapse due to the development of lesions.

In the lower part of the plant, symptoms occur include discoloration of rhizomes which initially appear light brown and progress to dark brown or black as when the infection worsens (Liu et al., 2021). As the rhizomes become waterlooged, their texture becomes soft and decayed due to tissue breakdown. Unlike infections caused by bacteria, rot caused by fungi does not produce odors (Archana et al., 2024).

2.3 Leaf spot

Leaf spot of ginger is a common disease caused by the soil-borne fungus *Phyllosticta zingiberi* which has led to significant reductions in rhizome production. Among the various diseases affecting ginger, this leaf spot is considered particularly destructive to its growth. Yield losses of approximately 13-66% have been recorded in ginger plants due to the severity of the infection (Merga, 2021). Primary infection occurs when fungal spores present in the soil and infected plant debris infect ginger under highly favorable conditions, specifically when humidity is high and temperatures range between 20ºC and 28ºC (Sood and Dohroo, 2005). The first case of this leaf spot disease was reported in India by Ramakrishnan in 1942. Subsequent cases have been reported in Ethiopia in 2019, the Philippines in 1966 and 1969, and Sarawak in 1972. Although *P. zingiberis* is the common fungus responsible for this infection, a study by a group researchers reported that leaf spot disease in ginger is also being caused by *Epicoccum sorghinum*, which infected ginger crops in Shandong province, China, in October 2020 (Yu et al., 2023). The symptoms were similar to those caused by *P. zingiberis*, confirming that *E. sorghinum* is also an agent of leaf spot disease.

Observations made by Ramakrishnan indicated that the disease was common between August and October, coinciding with the rainy season in many South Asian countries, where average temperatures range from 22ºC to 32ºC, giving favorable conditions for fungal growth. Research conducted by some researchers stated that leaf spot disease did not appear in June 2000 (Sood and Dohroo, 2005). However, the disease began to develop between July and August of the same year as heavy rains increased humidity, providing optimal conditions for disease development. They concluded that an optimal temperature of 25ºC is required for the development of *Phyllosticta* leaf spot.

The symptoms of ginger leaf spot disease showed that the leaf spots vary in size, averaging 9-10 mm in length and 3-4 mm in width (Nair, 2019). The shapes of the spots were typically round, oval, and elongated. The center of each spot is white, where the fungus resides, and is surrounded by a brown margin with a yellow halo. The center of the spot is thin and can be easily torn off. Initially, the spots are isolated from one another. However, further fungal infection occurs, the spots merge, forming a larger spot that can dry out the leaf completely. A report by some researcher described symptoms of leaf spot disease on ginger, which he observed in August 2014 (Abed-Ashtiani et al., 2016). He noted small scattered brown spots on leaves, along with hardened structures containing fungi that form black blotches on ginger plants cultivated in Bentong, Pahang. However, due to increased humidity, the lesions fused and became larger. As the lesions on the leaves become severe, they lead to foliar damage. This damage disrupts the photosynthesis process due to chlorophyll destruction, limiting the production of rhizomes (Merga, 2021). Consequently, this can result in decreased market availability for ginger.

2.4 Mosaic disease

Mosaic disease is caused by ginger mosaic virus, which is believed to belong to the cucumber mosaic virus (CMV) group. This viral infection causes significant major damage to ginger crops compared to diseases caused by ginger chlorotic fleck virus. A study conducted in Malaysia demonstrated that the virus identified as ginger mosaic virus is related to

CMV, as determine through RT-PCR detection (Muhammad et al., 2021). CMV is a single-stranded positive-sense tripartite RNA virus, with each RNA segment involved in the replication, translation, and movement of the virus (Eiras et al., 2004). Initially, CMV was first reported to cause disease in cucumbers and muskmelons in Michigan and New York in 1916. There have been several cases of CMV infecting ginger in seven states in Brazil, with all samples collected between 1996 and 2002 (Eiras et al., 2004). Over the decades, CMV has been identified as a plant virus with the widest range of hosts, infecting more than 1,200 species across 100 plant families, including ginger (Mochizuki and Ohki, 2012; Palukaitis et al., 1992). The virus is found in temperate zones but is primarily present in countries with tropical climates. CMV is transmitted by aphids and, occasionally, through seeds. When the virus enters a plant cell, the particles uncoated, and the genomic RNAs are translated to produce viral proteins (Villette et al., 2020). These proteins are essential for replication, which occurs in the tonoplast of the plant (Jacquemond, 2012).

Infection of CMV in ginger plants shows distinct symptoms, particularly on the leaves. The virus manifests as mosaic patterns with stripes accompanied by yellowing symptoms on the leaves (Muhammad et al., 2021). The mosaics display yellow and dark green patches on infected leaves. The plants physical usually appear stunted and dwarfed, and their leaves exhibit chlorosis (Ananthu, 2018; Mochizuki and Ohki, 2012). The leaves may also become wrinkled and curled, often taking on an irregular shape (Meenu and Jebasingh, 2020). CMV infection on ginger also affects the production of rhizomes, decreasing the economic demand for ginger. Observations of viral concentration in different parts of plants indicate that leaves and flowers have a higher concentration of the virus compared to rhizomes and the stems. Report of CMV infecting various plant species shows similar symptoms, for instance, mosaics appear on the leaf, accompanied by stunting and leaf deformation on infected tobacco crops (Kaplan et al., 1998). Another observation of CMV infection exhibited chlorosis followed by systemic mosaic formation and leaf deformation in a different tobacco species (Sclavounos et al., 2006).

3. Diagnosis of Disease

3.1 Real-time PCR

Identifying diseases caused by pathogens is particularly challenging when more than one pathogen is involved. The complexity of identifying the pathogens increases, especially when they exhibit overlapping symptoms (Jiang et al., 2022). Selecting an appropriate diagnostic technique is crucial for achieving accurate results regarding the causative agent of the disease. To address this, real-time PCR has been introduced as a widely used diagnostic technique for the detection and quantification of genetic material from various pathogens including bacteria, viruses, and fungi in plants (Grosdidier et al., 2017).

Unlike traditional PCR, which only detects the presence or absence of DNA, real-time PCR measures the quantity of DNA in real time during the amplification process. Moreover, traditional PCR requires post-PCR analysis and is more time-consuming than real-time PCR (Valasek and Repa, 2005). This diagnostic method uses fluorescent dyes or probes that emit signals during each cycle of the amplification step. These probes are specifically designed to target the PCR product and are labeled with a fluorophore, a molecule that emits photons, and a quencher, a molecule that absorbs photons from the fluorophore. The activity of *Taq* DNA polymerase on the probes leads to fluorescence emission during amplification as the quencher is separated from the fluorophore. This signal is measured by a machine called a real-time PCR cycler (Erkut et al., 2016; Kralik and Ricchi, 2017).

Two key principles of real-time PCR include the measurement of fluorescent intensity, which correlates with the amount of DNA present, enabling quantification (Bhargava, 2010; Mackay, 2002). The second principle of real-time PCR involves the cycle threshold (Ct) value, which indicates the number of cycles required for the fluorescent signal to surpass a predefined threshold (Okubara et al., 2005). The Ct value is inversely proportional to the initial quantity of target DNA in which lower Ct value indicates higher amounts of target nucleic acid and vice versa (Bhargava, 2010; Natarajan et al., 2023).

Real-time PCR, a fluorescence-based assay has shown promising results in detecting a wide range of organisms, including plant pathogens. This method is particularly valuable for diagnosing diseases caused by fungi and bacteria in crops like ginger (Mirmajlessi et al., 2015). Real-time PCR provides a rapid, sensitive, robust, and highly specific technique to identify soil-borne pathogens such as *Fusarium* spp. and *Phythium* spp which cause rhizome rot in ginger, especially when these pathogens require DNA extraction directly from soil or plant tissues (Kumar et al., 2023). For example, a study by group researchers demonstrated the use of real-time PCR with TaqMan fluorescence probes to detect *Ralstonia solanacearum,* the causative agent of bacterial wilt in ginger (Weller et al., 2000). Additionally, some researcher used phage amplification combined with real-time PCR assay to detect *Ralstonia solanacearum* in ginger (Kutin et al., 2009). Furthermore, a study used a real-time PCR assay in detecting *Ralstonia solanacearum* in ginger rhizomes that are sold in the Thailand market (Thammakijjawat et al., 2006). Thus, it can be concluded that real-time PCR is an effective diagnostic tool to detect pathogens in ginger with abilities to outperform traditional methods.

3.2 Enzyme-Linked immunosorbent assay (ELISA)

Unlike RT-PCR, which is used to detect and quantify nucleic acids, the Enzyme-Linked Immunosorbent Assay (ELISA) is designed to detect and quantify proteins such as antigens and antibodies (Tsurusawa et al., 2021). The targeted proteins that can be measured using ELISA include the viral or bacterial antigens. The principle of ELISA relies on enzyme-linked antibodies that produce a color change or fluorescence upon reacting with antigens associated with pathogens (Parnas and Linial, 1998). The sensitivity of ELISA is moderate, as it depends on the concentration of proteins present in the sample. Therefore, ELISA serves as an effective diagnostic tool for detecting various pathogens in ginger.

A method derived from ELISA, known as the Immunostrip method, can detect the *Ralstonia solanacearum* species within 30 minutes (Prameela and Suseela Bhai, 2020). Recent advancements in ELISA have focused on enhancing sensitivity and specificity using sandwich ELISA (Wang et al., 2021). This method involves adding a sample containing antigens to a solid surface where antibodies are immobilized on a microplate, allowing the antigens to bind to the antibodies. After washing the plate to remove unbound materials, an enzyme-labeled antibody is added to form a sandwich complex of antibody-antigen-antibody enzyme (Dita, 2021; Hayrapetyan et al., 2023). The substrate for the enzyme will be added, and any unbound antibodies is then washed away. The amount of product generated is proportional to the number of antigens in the sample (Aydin et al., 2025).

ELISA can achieve high sensitivity, with rates up to 100%, and specificity around 92.3% when detecting pathogens, making it a reliable diagnostic method for the early detection of infections (Aydin et al., 2025; Harvey, 1987). Additional advantages of using ELISA include rapid results that can be obtained within a few hours, along with its straightforward methodology using basic laboratory equipment, making it accessible for quick diagnostics.

A study by a group researcher utilized the ELISA method to detect *Ralstonia solanacearum* which causes bacterial wilt in ginger, using specific antibodies and, showing a positive color reaction at a concentration of 10^8 CFU.ml^{-1} (Kumar and Sarma, 2004). Another study by demonstrated good sensitivity of ELISA in detecting *Phythium* spp. and *Fusarium oxysporum*, which cause rhizome rot disease in ginger using developed antibodies at an absorption of 450 nm (Ray et al., 2018). Additionally, a study reported that the virus isolates from ginger plants exhibiting mosaic disease showed positive reactions with antiserum against CMV when tested using ELISA (Khan et al., 2012). Supporting this, used DAC-ELISA along with polyclonal antibodies specific to Cucumber Mosaic Virus (CMV), resulting in a positive reaction between the virus and the antibodies (Yosef et al., 2022).

3.3 Loop-Mediated Isothermal Amplification (LAMP)

LAMP is an isothermal amplification technology invented by the Japanese company, Eiken Chemical Co., Ltd in 1998. This technique is ideal and highly specific, especially for applications that require quick diagnostics. It is based on the activity mediated by *Bst* polymerase in auto-cycling and DNA strand displacement, aided by six primers that facilitate the amplification process (Nagamine et al., 2002). The reaction is carried out at a constant temperature of 60ºC, which is the optimum temperature Bst DNA polymerase activity. Unlike PCR which requires repeated heating and cooling steps, LAMP operates at a constant temperature of 60ºC, making the use of a thermocycler unnecessary. This characteristic makes LAMP preferable for field use (Iwamoto et al., 2003). Additionally, LAMP is cost-effective and can generate multiple copies of DNA in just 30 to 60 minutes.

A study conducted, utilized LAMP to amplify *R. solanacearum* causing bacterial wilt in mulberry samples collected in Zheijiang and Beijing, China (Huang et al., 2017). This suggests that LAMP effectively diagnoses the same bacterial species responsible for bacterial wilt in ginger. Amplification via LAMP demonstrated higher sensitivity with a 10-fold dilution series of pure cultures of the bacterial strain, with a detection limit 100 times higher than conventional PCR, at a value of 2.2 x 10^2 CFU.ml^{-1}. Furthermore, LAMP is not limited to diagnosing bacteria, it can also detect viruses. A study indicated that Cucumber Mosaic Virus (CMV), which causes stunted disease in plants, can be diagnosed using LAMP (Bhat et al.,

2013). This study focused on black pepper plants, which exhibited similar symptoms to those of ginger infected with CMV. In a recent study, supporting LAMP's capability to diagnose viruses causing chlorotic fleck disease in ginger, the RT-LAMP technique was employed to identify Ginger Chlorotic Fleck-associated Virus 1 and Ginger Chlorotic Fleck-associated Virus 2 (Naveen and Bhat, 2020). Naveen and Bhat highlighted that RT-LAMP was 1000 times more sensitive than conventional PCR. Additionally, LAMP provided rapid detection for *Phythium* spp. which primarily causes soft rot in ginger, with a detection limit of 100 fg, and results can be obtained within 30 minutes in the field (Yosilia et al., 2023).

3.4 Machine Learning

Over the past few years, machine learning has been widely used in various fields. With advancements in technology and the availability of datasets, the use of machine learning has increased significantly. Machine learning enables predictions based on data input into the system. Additionally, it serves as an automated diagnostic a technique derived from artificial intelligence, providing rapid diagnoses while enhancing accuracy, efficiency, and data accessibility (Petrillo et al., 2019). The rapid identification of diseases using machine learning has addressed to threats to food security and promoted the production of healthy crops. For instance, through deep learning, 14 crop species and 26 types of diseases were identified with an accuracy of 99.53%, according to a study (Mohanty et al., 2016). There are various algorithms in machine learning for diagnosis, including supervised learning which focuses on using labeled datasets to train models that predict outcomes (decision trees); unsupervised learning, which identifies patterns (clustering); and deep learning, which uses neural networks to analyze complex data patterns effectively, particularly in image recognition tasks. Despite having higher accuracy and efficiency, machine learning also offers benefits such as cost-effectiveness and scalability, making it suitable for diagnostic processes in large and diverse populations (Ahsan et al., 2022; Fatima and Pasha, 2017).

Among various machine learning methods, deep learning has gained significant interest in recent years. The algorithm mainly focuses on tasks related to image recognition, language processing and speech recognition (Sharada et al., 2023). A widely used application of deep learning algorithm is Convolutional Neural Networks (CNN), which have the ability to recognize images, classify them, and detect object, making them suitable for disease diagnosis. CNN is structured in a series of layers that work together to analyze visual data. The steps involved include the input layer, convolutional layer, pooling layer, additional convolutional layers, flattening layer, fully connected layer, output layer, and training process.

In agriculture, machine learning is also being applied to diagnose diseases in crops like ginger. A study utilized a deep learning approach to detect diseases in ginger after collecting 7014 images of ginger plants (Yigezu et al., 2022). This test achieved an accuracy of 95.2% in detecting bacterial wilt disease in ginger. Additionally, a study by a group researcher utilized neural networks based on convolution (CNN) and random forest techniques for ginger leaf classification (Rana et al., 2024). Through multiple training with ginger leaf datasets, accurate classifications of diseases were achieved. In this study, a group research focused on eight distinct diseases, including leaf spot caused by *Phyllosticta zingiberi*, bacterial wilt caused by *Ralstonia solanacearum*, rhizome rot caused by *Phythium* spp., and another type of bacterial wilt caused by *Fusarium oxysporum*. The results indicated that CNN is capable of recognizing recognize each disease with precision rates ranging from 91.39% to 94.44%.

4. Control of Pathogens and Disease in Ginger

Numerous pathogens cause diseases in ginger, leading to reductions in both yield and quality of ginger crops. Therefore, effective management to control these pathogens and prevent the spread and severity of these diseases affecting ginger crops. Recent findings indicate several control mechanisms can be applied to manage these diseases, including cultural practices, soil and vector management, biological control, and chemical control.

4.1 Cultural Practices

Cultural practice methods focus on crops, tools, and field management, ensuring that everything is free from pathogens that might infect the plants. The most effective way to manage infectious pathogens in ginger is to plant disease-free rhizomes and select disease-free seeds. By ensuring that planting materials are free from pathogens, the initial infection can be prevented. Additionally, routine field sanitation is important for scouting for plants that appeal with symptoms and remove them, which will help prevent the spread of pathogens (Abayneh, 2024). Furthermore, practicing crop rotation, which by alternating the planting of ginger with non-host crops will aid in breaking the disease cycle and reducing the pathogen population in the soil (Yadav, 2023). To reduce the severity of leaf spot disease, a study in India stated that shade plays a significant role in providing favorable conditions for ginger cultivation, resulting in lower disease incidence compared to open cultivation (Merga, 2021).

4.2 Soil Management and Vector Management

One of the techniques that aid in soil management is soil solarization, which involves covering soil with plastic sheets to trap heat from solar. This process helps in raising the soil temperature to levels that can kill pathogens. A study indicated that disease incidence was reduced along with an increase in ginger yield, after utilizing the soil solarization technique in Kerala, India (Dake, 1995). By practicing proper soil management, diseases caused by soil pathogens can be reduced from 20% to 80% (Larkin, 2015).

For viruses that rely on insects as vectors, managing vector populations is crucial to prevent the spread of diseases. Aphids are vectors that help spread viruses causing diseases in ginger (Meenu and Kaushal, 2017). Therefore, introducing insect predators of aphids can help reduce the aphid population in crop fields. Additionally, aphids are often introduced through wind events on equipment, plant materials, and other organisms. Cleaning equipment with disinfectants can help reduce the pathogen population (Bhat, 2024).

4.3 Biological Control

Biological control, including the use of microorganisms as a strategy to manage infections, is one of the most environmentally friendly methods. *Bacillus velezensis* has been identified as become an effective biocontrol agent against *Ralstonia solanacearum*, possessing traits that allow it to produce antibacterial metabolites that suppress the activity of the pathogen affecting ginger (Cui et al., 2024). Moreover, for biocontrol of *Fusarium oxysporum*, *Trichoderma* spp. Has the potential to decrease infections in ginger plants. These fungi possess antibiotic properties and digestive enzymes that can break down the cell walls of pathogens. Observations made showed that *T. viride* and *T. harzianum* exhibited 68.3% and 66.7% effectiveness, respectively, as aggressive antagonists against *F. oxysporum* (Khatso and Ao, 2013). The examination revealed the hyphae of these *Trichoderma* spp. surrounded the hyphae of *F. oxysproum*, resulting in cell wall degradation and coagulation of the pathogen's cellular components. Furthermore, seed treatment using *Trichoderma* spp. also aids in controlling rhizome rot in stored ginger (Dake, 1995; Khatso and Ao, 2013).

4.4 Chemical Control

Chemical control is widely used as it is one of the most effective methods for managing diseases in ginger. Recent findings indicate that various chemical applications can be used, including fungicides, bactericides, seed treatments, and soil drenching. A report by Singh (2015) stated that the use of 0.1% Carbendazim to control *Phyllosticta* leaf spot on ginger was the most effective fungicides compared with four other fungicides: Copper Oxychloride, Mancozeb, Thiophanate Methyl, and Metalaxyl (Singh, 2015). The fungicides were sprayed on ginger leaves exhibiting symptoms twice a month and were found to effectively reduce the disease in ginger (Bandyopadhyay et al., 2015).

In addition, a study investigated the use of antibiotics such as gentamicin, tetracycline, streptomycin, and ampicillin in eliminating bacterial infections, which are effective for ginger cultivation (Markos and Feyissa, 2020). Treatment using Ridomil Gold, mixture of Metalaxyl and Mancozeb at 0.2% for both seed treatment and soil drenching, was effective in controlling the rhizome rot disease, with only 15.63% of ginger infected, while 84.37% showed positive results for rhizome germination (Ayub et al., 2010). The addition of Darsbun to Ridomil resulted in a higher yield of 32.20 t/ha and the least number of infected plants at 4.72 (Ghimire et al., 2022). According to a study, seed treatment and soil drenching using a mixture of Ridomil Gold, Clorox (10%), and stable bleaching powder (20kg/ha) increased the percentage of rhizome germination (96%) with only 6% disease incidence (Islam et al., 2022).

5. Conclusion

Ginger (*Zingiber officinale*) is an important crop that faces serious threats from various pathogens causing diseases, including bacterial wilt caused by *Ralstonia solanacearum*, rhizome rot caused by *Fusarium* and *Phythium* spp., leaf spot disease caused by *Phyllosticta zingiberi*, and mosaic disease caused by Cucumber Mosaic Virus and Ginger Mosaic Virus. These diseases can lead to reduced reducing ginger yield and quality, threatening food security, and the economic viability of ginger farming.

Accurate diagnosis is vital for effective disease management in ginger

cultivation. Therefore, monitoring diseases caused by these pathogens is crucial, especially with advanced diagnostic techniques such as RT-PCR, ELISA, and LAMP, which provide accurate and quick detection of pathogens. Recent advancements in machine learning have further improved disease diagnosis in ginger, allowing for rapid and more accurate identification of diseases using multiple training datasets.

However, effective management strategies are essential to counter these threats to ginger crops. Cultural practices such as using disease-free planting materials, maintaining field sanitation, and rotating ginger crops with non-host plants can help prevent further infections. Soil management and vector management are pivotal in preventing initial infections, using soil solarization and introducing predators, respectively. Chemical control with fungicides and bactericides, is also widely used as it is one of the most effective control practices. Additionally, environmentally friendly methods such as biological control should gain more recognition, as they can help reduce infections without affecting the soil pH or damaging beneficial insects.

In summary, continuous research on diseases and the pathogens that caused them can aid in managing infections in ginger crops and preventing diseases from becoming severe. Effective disease management in ginger is crucial, as ginger is one of the most important crops in Malaysia, benefiting local farmers and meeting high market demand in the country. Further improvements in research technology and control measures can reduce infections while increasing ginger yield and quality, making Malaysian ginger more accessible in the global market.

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