Advances in Agricultural Technology & Plant Sciences
ISSN: 2640-6586
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Research Article
Volume 7 Issue 2

Agronomic Practices for Management of Ginger Bacterial Wilt Disease: A Review

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Received Date: September 27, 2024; **Published Date:** October 21, 2024

Abstract

Ginger is one of the most important spices, particularly for small-scale farmers in Ethiopia. However, bacterial wilt is a major constraint to ginger production, and it was reported for the first time in 2012. The disease is caused by the bacteria *Ralstonia solanacearum*. Common symptoms in infected plants include wilting, stunting, yellowing of foliage, and rhizome rot. The disease is now widespread across all ginger-growing regions worldwide, spreading through soil, water, infected rhizomes, and plant debris. A major challenge in managing bacterial wilt has been the lack of effective control methods. This review primarily focuses on recent advances in control measures, including agronomic and cultural practices such as soil amendment, rhizome treatment, and other cultural practices. Soil and rhizome *solarization* has proven to be a cost-effective method that is compatible with other pest management tactics. Additionally, the use of organic matter, such as crop residue and animal manure, which improves the physical, chemical, and biological properties of soil, has been studied as an inducer of *suppressiveness* to *R. solanacearum*. The application of certain plants and their essential oils as bio-fumigants has also been examined as an alternative approach to managing bacterial wilt as part of an integrated disease management system. Crop rotation, tillage, and field sanitation play vital roles in disease management. Furthermore, other farm practices, such as the use of healthy seeds, cultivation in disease-free areas, cover crops, bio-mulch, and regular field inspection, also contribute to the suppression of this pathogen. Overall, employing agronomic and cultural practices in combination with an integrated pest management strategy offers a promising approach for controlling bacterial wilt and ensuring sustainable ginger production.

Keywords: Ginger; Bacterial Wilt; Disease Management; Agronomic Practices; Integrated Pest Management

Abbreviations

RH: Relative Humidity; BOFs: Bio-Organic Fertilizers; DAD-ELISA: Double Antibody Sandwich Enzyme-Linked Immunosorbent Assay; PCR: Polymerase Chain Reaction; OM: Organic Matter.

Introduction

Ginger (*Zingiber officinale* Rosc.), belonging to the family *Zingiberaceae*, originated in Southeast Asia, with its main center of diversity in Indo-Malaysia [1]. It is an important commercial crop grown for its aromatic rhizomes, which are used both as a spice and in traditional medicine [2]. Today, ginger is cultivated in many tropical and subtropical regions worldwide. In Ethiopia, it is one of the most significant spices, playing a crucial role in the livelihoods of small-scale farmers [3]. The crop is primarily grown in the wetter areas, particularly in the western, southern, and southwestern parts of the country, at altitudes below 2,000 meters above sea level. In major production areas, about 85% of farmers and 35% of the total arable land are dedicated to ginger cultivation [4]. However, in recent years, ginger production has been severely affected by a devastating disease called bacterial wilt [5]. The outbreak of this disease was reported for the first time in 2012 Habetewold K, et al. [6]. Prior to the outbreak of this disease, Ethiopia generated up to USD 22 million in a single year from ginger exports [7]. Following the sudden outbreak of bacterial wilt disease, the production and supply of ginger in the country have declined sharply. In the same year of the disease outbreak, an estimated incidence of 80-100%, which gave rise to up to 90-100% crop loss, was registered in the fields Habetewold K, et al. [6,8].

Bacterial wilt (*Ralstonia solanacearum*) is a major constraint for production of edible ginger (*Z. officinale* R.) in many tropical and subtropical regions of the world [6]. The disease is caused by the soil-borne bacterial pathogen *R. solanacearum* race 4, which has caused major economic losses to the edible ginger industry [9]. The *R. solanacearum* race 4 biovar 3 strains is the causal agent for ginger bacterial wilt in Ethiopia [8]. According to Hussain, M, et al. [10], the disease can cause up to 100% yield losses in many ginger-growing regions under conducive conditions. The first ginger bacterial wilt disease was reported from India in 1941 by Thomas, and then lots of reports came from the rest of the world. In Ethiopia, the first bacterial wilt syndrome on ginger was reported from Bench Maji Zone Bebeka coffee estate farm in 2012, then progressed to the neighboring zone Sheka within a short period of time and caused up to 67% yield loss [6]. Since its first report, the outputs of ginger production from major growing areas were significantly declined and the volume has been delivered to the central market also greatly reduced. Indirectly, the economic and social aspects of the small-scale farmers and growers involved in ginger production have also been negatively affected.

Bacterial wilt of ginger is widespread and exceedingly destructive in several countries, a situation made worse by the easiness with which the pathogen is carried within the planting material. Moreover, the pathogen can also spread by water, latently infected planting materials and soil [11]. Once fields became infested with the pathogen, they were unsuitable for cultivation of edible ginger because the inoculum persisted on plant debris, weeds, and farm equipment [12]. However various control strategies were developed to control and suppress this disease including agronomic and cultural control practices, host-plant resistance, biological control, chemical control [13]. To this end, the objective of this paper to review the agronomic practices on ginger bacterial wilt disease management.

Literature Review

Causes and Symptoms of Ginger Bacterial Wilt

The disease is caused by *Ralstonia solanacearum* race 4 Paret M, et al. [9], although various races have also been reported. Cunniffe NJ, et al. [14] found that *R. solanacearum* race 3 caused slow wilt, while race 4 led to rapid wilting and death of infected plants. Additionally, race 3 was found to be restricted to ginger, whereas race 4 exhibited a wider host range, affecting plants such as tomato, potato, *Zinnia elegans*, *Capsicum frutescens*, *Physalis peruviana*, and eggplant [15]. *Ralstonia solanacearum is characterized by the sudden wilting of foliage, with younger plants being more severely affected.* On the collar region, water soaked patches or linear streaks appear. These symptoms are followed by yellow to bronze coloration of margins of the lower-most leaves which gradually progresses upwards Habetewold K, et al. [6,15]. At later stages, the leaves become flaccid with intense yellowish bronze color and droop ultimately exhibiting typical wilt symptoms. In the infected plants, leaf sheaths look yellowish to dull green. *The pseudostem becomes soft and completely rots, causing the diseased shoots to break off easily from the underground rhizome at the soil line*. At advanced stage the *pseudostem* appears slimy and *dries out very rapidly, within 5 to 10 days* Habetewold K, et al. *[6].* The plants which are infested by the disease stand persistently and do not collapse. In the early stages of infection, the ginger rhizome shows a grayish-brown discoloration. The rhizome becomes soft, water-soaked and rotten, when it pressed and immersed in a clean water a milky bacterial exudate oozes outs [6,15,16].

Environmental Factors Influencing Disease Outbreak

The prevalence of ginger bacterial wilt varies based on differences in geography, agro-ecology, and the prevailing weather conditions of the growing area [13]. According to Habetewold, K, et al. [6], in Ethiopia, the onset of the disease occurs from the end of June to mid-July and continues until October, which coincides with the country's main rainy season and the dominance of warm, humid weather. Increased rainfall during July-September facilitates the transport of active inoculum to nearby fields through rain runoff and farm activities, thereby increasing the incidence, severity, and distribution of the disease [17]. However, after October, moisture, temperature, and wilt incidence dramatically decrease. In Ethiopia, the severity and devastation of the disease in major ginger producing areas were due to the ideal weather conditions for bacterial epidemics and the use of latently infected seed rhizomes as planting materials.

Agronomic Management of Ginger Bacterial Wilt

Bacterial wilt is a major problem and a production constraint for ginger and other vegetable crops [18]. It is difficult to control bacterial wilt due to its wide host range, genetic variability, complex epidemiology, diverse modes of transmission [12,19]. Various agronomic practices as a control measures have been reported to combat this disease such as selection of healthy seed rhizomes and fields, selection of resistant variety, seed rhizome treatments and soil amendment. Moreover, other practices including crop rotation, cover crops, tillage, field sanitation, weeding, insect pest control, mulching, good drainage, field inspection, and quarantine measures have also been suggested by Sharma B, et al. [19] and Kumar, A, et al. [20]. Some of these agronomic and cultural control methods are discussed in detail below

Seed Rhizome Treatment

Heat and Solarization: As noted earlier, contaminated planting material is a primary source of inoculum for field infection. Disinfection of rhizomes using solar radiation, known as rhizome solarization, has been developed as a method for managing bacterial wilt [20]. This technique is considered one of the most eco-friendly and energy-efficient methods available for rhizome treatment. According to Wong C, et al. [21], *R. solanacearum* was eliminated from ginger rhizomes when exposed to heat for 30 minutes at 50°C. Solar radiation raises the temperature of rhizomes, particularly in the vascular region [22]. Plants emerging from solarized rhizomes often escape disease due to the in-situ killing of the pathogen in the seed rhizome [20]. However, a major source of variability in heat buildup and pathogen elimination is the size and shape of the rhizome [18]. Larger rhizomes tend to experience greater heat buildup due to their larger surface area, which traps more sunlight and results in higher internal temperatures [22]. Kumar A, et al. [20] found that 2 hours of rhizome solarization are generally sufficient to achieve the requisite temperature inside the vascular tissue where the pathogen resides. This temperature increase may reduce the number of viable bacteria in the rhizome. Overall, these studies indicate that rhizome solarization effectively disinfects rhizomes infected with *R. solanacearum*, whether the infection is artificial or natural.

Hot air and water: The use of non-saturated heated air is a promising method for disinfecting ginger seed rhizome pieces. According to Wong, C, et al. [21], exposing ginger seed pieces to hot air at 75% relative humidity (RH) until their internal temperature reaches 50°C for 30 minutes effectively destroys the bacterial wilt pathogen while causing minimal injury to the rhizome. This treatment does not adversely affect germination or subsequent growth. Kumar A, et al. [18] note that for effective heat treatment, the exposure time must be sufficient to penetrate the seed piece completely but not so prolonged as to cause injury to the host. Kumar A, et al. [23] reported that soaking ginger seed in hot water at 50°C for 10 minutes is a standard pre-planting procedure in Hawaii. However, shorter exposure times may result in inadequate heat penetration, while longer periods can cause heat injury and stunt crop growth [23]. Several studies have demonstrated that heat treatment can kill pathogens without compromising the viability of the planting material [21,24]. Additionally, selecting uniformly sized seed pieces helps maintain consistent thermal gradients during treatment. Both hot air and water treatments also serve to release the seed pieces from dormancy.

Soil Amendment

Soil solarization

A number of physical control methods have been proven effective against *Ralstonia solanacearum* in soil, including solarization, hot water treatments, cold temperatures, and bio-fumigation [25]. Soil solarization prior to planting has been widely used to control soil-borne pathogens and pests in various crops, including potato, ginger, onion, carrot, and peanut [18]. Huang, Y, et al. [25] reported that solarization induces complex biological, physical, and chemical changes that enhance plant growth, quality, and yield for several years. The success of soil solarization is based on the fact that most plant pathogens and pests are mesophiles, which do not produce heat-resistant spores and are unable to survive long periods at high temperatures [26]. According to Kumar, A, et al. [18], polyethylene is a suitable cover for solarization because it transmits the germicidal components of sunlight. The death of organisms at high temperatures involves the inactivation of enzyme systems, particularly respiratory enzymes. In another study, soil solarization using transparent plastic mulches for 28 days prior to planting ginger significantly reduced the incidence of bacterial wilt [27].

Soil bio-fumigation

Bio-fumigation refers to the agronomic practice of using volatile chemicals released from plant residues to suppress soil-borne plant pathogens [26]. The antimicrobial activity of various plant essential oils and their volatile components against plant pathogenic bacteria, fungi, nematodes, and viruses has been extensively studied [28], with promising results. Nazzaro, F, et al. [29] reported that certain essential oils, including thymol, reduce *Ralstonia solanacearum* population density and bacterial wilt incidence in tomatoes, while also increasing plant shoot and root weights. In another study, conducted under laboratory conditions, thymol and palmarosa oil provided complete protection against bacterial wilt in tomatoes by reducing the pathogen population to undetectable levels [30]. Similar results were observed under both greenhouse and field conditions [31]. According to the author, the use of plant essential oils as bio-fumigants has been explored as part of an integrated disease management system for bacterial wilt.

Additionally Momma N, et al. [32] reported that combining soil bio-fumigation with solarization significantly reduced the incidence of bacterial wilt. Messiha N, et al. [33] also found that biological soil disinfection combined with solarization using airtight plastic reduced *R. solanacearum* populations by more than 90% in soil. In Ethiopia, some aromatic plants and herbs have been tested as soil disinfectants and bio-fumigants to control ginger bacterial wilt. This work began in late 2015 at the Teppi Agricultural Research Center, where lemongrass (*Cymbopogon citratus*) and Chinese chive (*Allium tuberosum*) were planted in bacterial wilt-infected fields. These aromatic plants helped create an unfavorable environment for *R. solanacearum* in the soil, thereby reducing its population and decreasing the incidence and severity of the disease.

Organic Amendments

Amending agricultural soils and soilless growing media with organic matter provides plant nutrients and enhances the natural suppressiveness of the soil against soil-borne pathogens [34]. Bonanomi G, et al. [35] reported that the addition of organic amendments, such as animal manures and industrial by-products, is a well-documented strategy for increasing disease suppression in soils. Organic amendments directly impact plant health and crop productivity. According to Bonanomi G, et al. [35], the degradation of organic matter in soil can affect the viability and survival of pathogens by restricting available nutrients and releasing natural chemical substances with varying inhibitory properties. Moreover, organic amendments have been shown to stimulate the activities of microorganisms that are antagonistic to pathogens [26]. The carbon released during the degradation of organic matter increases soil microbial activity, thereby enhancing competitive effects in the soil [35]. Additionally, frequent applications of organic materials, such as manure or compost, eventually result in higher substrate availability for competitors, reducing the growth of pathogens in the rhizosphere and decreasing their infection rates [36]. Yadessa, et al. [37] reported that amending topsoil with different types and rates of organic amendments can suppress pathogen survival in the soil and reduce bacterial wilt severity.

In another study, the incorporation of household compost was found to reduce bacterial wilt incidence and severity [26]. Ghini, R, et al. [38] also reported that sewage sludge, being a rich source of organic matter and nutrients, enhances disease suppression caused by *R. solanacearum*. Animal manure has traditionally been used as a nutrient source and can significantly improve crop yields. While many studies have reported that animal waste controls plant diseases, few have specifically addressed its effectiveness against bacterial wilt disease. Islam, T, et al. [39] observed suppression of bacterial wilt in soils amended with poultry manure and farmyard manure. Other studies have shown that incorporating cow dung manure and pig slurry reduces bacterial wilt incidence and severity [33]. However, Van Elsas, J, et al. [40] noted that the suppressive effects of organic amendments on *R. solanacearum* vary with soil type, texture, temperature, organic matter content, pH, microbial communities, moisture content, and dissolved organic carbon content. According to Janvier, C, et al. [34], the effectiveness of organic matter in suppressing plant pathogens depends on: (i) the plant-pathogen combination, (ii) the rate of application, (iii) the nature/type of amendment, and (iv) the decomposition stage of the organic matter.

Crop Residue Management

According to Alabouvette, C, et al. [41], residue management, particularly the retention of crop residues in situ, can have conflicting effects on disease. Increasing evidence suggests that residue retention can enhance levels of general suppression in soils. This effect is linked to high levels of microbial activity, which depend on substantial organic matter (OM) input into soils [41]. Several studies have reported that bacterial wilt can be suppressed by plant residues from various plant species. For instance, residues from chili (*Capsicum annuum*) [42], Chinese gall (*Rhus chinensis*), wood wax tree (*Toxicodendron xylosteoides*) [43], clove (*Syzygium aromaticum*) [44], cole (*Brassica* sp.) [45], eggplant (*Solanum melongena*) [46], eucalyptus (*Eucalyptus globulus*), lemon grass (*Cymbopogon citratus*), guava (*Psidium guajava* and *P. quinense*) [47], neem (*Azadirachta indica*) [48], pigeon pea (*Cajanus cajan*), thyme (*Thymus* spp.) [29], and worm killer (*Aristolochia bracteata*) [49] have all been shown to suppress bacterial wilt.

Several studies have demonstrated the successful application of organic matter against bacterial wilt in both greenhouse and field conditions. Cardoso, S, et al. [50] reported that incorporating freshly cut aerial parts of both pigeon pea (*Cajanus cajan*) and crotalaria (*Crotalaria juncea*) at concentrations of 20-30% and incubating for 30 days resulted in complete suppression of bacterial wilt under greenhouse conditions.

Cardoso S, et al. [50] suggested that the possible mechanisms of action for plant residues include antimicrobial activities, as well as the indirect suppression of pathogens through improved physical, chemical, and biological soil properties. Six J, et al. [51] found that populations of cellulolytic organisms are higher in soils where crop residues are retained. Other studies have shown that residue retention also favors cellulolytic *Trichoderma* species, many of which are antagonistic to plant pathogens [52]. Yadessa, et al. [37] reported that soils amended with 10% coco peat and 1% green compost completely inhibited infection by *R. solanacearum*, while disease severity reached 43% in the unamended control soil. Andriantsoa R, et al. [53] also found that about 50% of tested cruciferous plant residues reduced *R. solanacearum* populations in the soil. However, retaining infected residues can sometimes increase the inoculum potential of pathogens that survive in the residue.

Cultivation and Fertilization

Proper and timely application of nutrients is a key mechanism in pest management within agro-ecosystems [37]. Elements in the cell walls can influence plant susceptibility or resistance to pathogen infections, and silicon is considered a beneficial element for plants and higher animals [36]. Kiirika L, et al. [54] reported that the combined application of silicon and chitosan reduced the incidence of bacterial wilt in tomatoes by inducing resistance. Calcium (Ca) is another well-known nutrient that suppresses disease, as noted by Yuliar, et al. [55]. Ciard et al. [56] also observed that increased concentrations of Ca in plants reduced both the severity of bacterial wilt and the population of *R. solanacearum* in tomato stems. Additionally, an increase in Ca uptake by plant shoots was correlated with lower levels of disease severity [56]. Lemaga B, et al. [57] reported that the application of nitrogen (N) + phosphorus (P) + potassium (K) and N + P (at a rate of 100 kg/ha for each fertilizer) reduced bacterial wilt by 29% and 50%, respectively. Furthermore, the combined application of rock dust and commercial organic fertilizer also reduced bacterial wilt incidence in tomato plants [58]. According to this study, higher soil pH and Ca content were key factors in controlling bacterial wilt through rock dust amendment.

Moreover, efficient soil management generally improves the composition and activity of soil micro biota, thereby enhancing the soil's biological control capacity [40]. **Prasad R, et al.** [59] found that a high dose of nitrogen applied as ammonia compounds to sandy soil was more effective in reducing bacterial wilt severity than nitrates. Islam T, et al. [39] reported that bacterial wilt incidence was suppressed in farmyard manure-amended soil when the application rate exceeded 4%, with an 8% application rate being the most effective. The usefulness of bio-organic fertilizers (BOFs) in controlling soil-borne plant diseases has also been investigated. Qiu M, et al. [60] found that BOF application minimized wilt disease incidence, maximized biomass production, and altered the microbial community structure. Wei Z, et al. [61] similarly reported that applying BOF significantly reduced disease incidence and *R. solanacearum* populations under both greenhouse and field conditions. On the other hand, organic matter inputs can sometimes lead to negative effects such as temporary oxygen depletion, denitrification, nitrogen immobilization, and pathogen stimulation [62]. Therefore, understanding the type and optimal rate of organic amendment that results in positive effects on disease suppression and plant growth is crucial for farmers.

Cultural Practices

Crop Rotation

Crop rotation with non-host plants is a widely used strategy to reduce disease incidence and is effective against bacterial wilt caused by *R. solanacearum*. The choice of rotation crops varies by region and pathogen strain [63]**.** Priou S, et al. **[64]** found that rotating with non-host plants, such as cereals and gramineous pastures, significantly reduces *R. solanacearum* populations in the soil. It is crucial to remove volunteer ginger plants by uprooting them to prevent further disease spread. While rotation with crops like *Allium* species (onion, garlic, leek) and *Brassicaceae* (cabbage, cauliflower) can be effective, limitations in land availability and marketability of crops can make this challenging for farmers [64]. These crops also help in eliminating weeds and volunteers that harbor the pathogen.

Legumes, such as *Fabaceae* (pea, bean), are also beneficial as rotation crops for ginger due to their nitrogen-fixing properties, which enhance soil fertility [64]. Additionally, cucurbitaceous crops (pumpkin, cucumber, zucchini) are not hosts for *R. solanacearum* and can be used in rotations. Chinese chive (*Allium tuberosum*) has been shown to reduce bacterial wilt incidence in tomato by approximately 60%, likely due to its root exudates that inhibit pathogen infection [65]. This crop is now being used in our country to control ginger bacterial wilt. *R. solanacearum* can survive in soil for up to 161 days [66]. The time required for eradication varies by location. In cases where suitable rotation crops are not available, leaving fields fallow can reduce wilt incidence, though this approach may not always align with farmers' economic interests.

Selection of Healthy Seed Rhizomes

The use of rhizomes collected from previously disease-affected areas as planting material often results in severe disease [18]. This underscores the importance of using pathogen-free seed to prevent disease outbreaks. According to Supriadi K, et al. [67], the most effective approach is to plant pathogen-free rhizomes in pathogen-free soil to avoid or prevent bacterial wilt epidemics, especially in the absence of effective chemical and biological control methods. However, pathogen-free rhizomes are not always readily available to all farmers due to the scarcity of seed material during peak planting seasons, particularly for crops like ginger, which require more than one ton of seed rhizome per hectare of land.

Selection of Disease Free Field

Site selection is crucial for the successful control of bacterial wilt in ginger. It has been observed that ginger grown in soil with no history of bacterial wilt often results in healthy crops, provided the rhizomes are free from the pathogen [18]. According to Supriadi K, et al. [67], ginger is traditionally cultivated in previously fallowed soil, virgin forest soil, or rubber plantations after 20 to 25 years of rubber cultivation in India. This long crop rotation often results in healthy ginger crops. Another alternative is to plant ginger underneath perennial trees or in social amenity forests with regulated shade [67]. Kumar A, et al. [18] also noted that soil can be tested for the presence of the pathogen using sensitive methods such as polymerase chain reaction (PCR). Techniques like double antibody sandwich enzyme-linked immunosorbent assay (DAS-ELISA) and PCR have been standardized for detecting the pathogen in soil [18,64].

Cover Crops

Cover crops are widely used in agriculture and can take various forms. According to Alabouvette, C, et al. [41], the most common type is green manure crops, which are grown to be incorporated back into the soil to enhance organic matter (OM) and nutrient levels. The effects of cover crops on soil biota are similar to those of rotation crops, residue retention, or organic amendments. These effects include providing additional substrate and niche diversity for soil biota, as well as the release of ammonia [41]. However, cover crops should be considered a valuable soil health management strategy on their own. Huang Y, et al. [68] reported the use of green manure crops to manage diseases in green beans. However, the effectiveness of cover crop species varied widely, even among closely related plants, indicating that the effect was not solely due to OM inputs. In addition to stimulating microbial activity, green manure crops often have bio-fumigant properties, as seen with brassicas and some legumes [41]. Currently, lemon grass and Chinese chive are being used as cover crop bio-fumigants to manage ginger bacterial wilt in our country (Figure 1).

Figure 1: Chinese chivu (left) and lemon grass (right) bio-fumigant planted on bacterial wilt infected field at Teppi Agricultural Research Center.

Tillage

Soil disturbance through tillage has various effects on plant diseases. Tillage is expected to influence soil suppressiveness due to its impact on the activity and diversity of soil micro flora [41]. According to **Giller, K, et al.** [69], tillage can reduce bacterial biomass and diversity in the soil, potentially due to its effects on soil aggregation. Priou S, et al. [64] reported that exposing plowed soil to summer heat in very warm areas also decreases soil infestation by *R. solanacearum*. Additionally Khangura R, et al. [70] noted that root rots caused by *R. solani* are generally less severe after tillage compared to direct drilling, and this effect has been used as a disease management strategy. The effects of tillage on disease appear to act directly on the pathogen, with no evidence yet of effects on other components of the soil biota. However, Alabouvette C, et al. [41] highlighted that determining the effects of tillage on soil receptivity or suppressiveness is complex because different tillage treatments are often confounded with other aspects of crop management. Comparisons between 'conventional' cultivation and organic, low-input, or conservation tillage systems often mix tillage and residue management effects. More experimentation is needed to isolate the effects of tillage alone on the biological suppression of soil-borne diseases.

Selection of Resistant Varieties

Plant resistance is one of the most effective methods for controlling bacterial wilt (BW). According to Yuliar, et al. [55], using cultivars resistant to bacterial wilt is considered the most economical, environmentally friendly, and effective method of disease control. However, breeding for resistance has primarily focused on crops of significant economic importance, such as tomato, potato, tobacco, eggplant, pepper, and peanut, and is influenced by several factors [71]. These factors include the availability and diversity of resistance sources, genetic linkage between resistance and other agronomic traits, differentiation and variability in pathogenic strains, the mechanisms of plant-pathogen interactions, and breeding or selection methodologies [13]. According to Prasath, D, et al. [72], no resistance sources to *Ralstonia*-induced bacterial wilt have been identified within the *Zingiber* genus. This is attributed to a lack of genetic variability among accessions for disease resistance, which is a major bottleneck in ginger genetic improvement.

Ravindran, P, et al. [73] reported that resistance breeding in ginger is limited to germplasm screening because it is an obligate asexual crop. The search for resistance has extended to other closely related genera in the *Zingiberaceae* family, such as *Curcuma amada*, *C. longa*, *C. zedoaria*, *C. aromatica*, *Kaempferia galanga*, *Elettaria cardamomum*, *Zingiber zerumbet*, and *Z. officinale*, for their reaction to *R. solanacearum* race 3 (ginger-specific strain) [72]. Notably Prasath D, et al. [74] found that Indian mango ginger (*C. amada* Roxb.) exhibited significant resistance to *R. solanacearum* pathogens. This high level of resistance in *C. amada* offers an opportunity to develop bacterial wilt resistance in ginger [72]. However, Yuliar, et al. [55] noted that resistance to bacterial wilt in many crops is often negatively correlated with yield and quality. Consequently, resistant cultivars may be poorly received due to other agronomic traits and may not be widely accepted by farmers or consumers. Future breeding efforts are expected to focus on enhancing bacterial wilt resistance through biotechnology approaches to improve yield and develop effective resistant cultivars.

Field and Farm Tools Sanitation, and Weeding

Crop sanitation and cultivation measures aim to limit pathogen survival and dissemination. After harvesting a bacterial wilt (BW)-infested crop, ginger plant residues must be removed from the field and buried deep, down-slope, and far from irrigation canals and alternatively, they can be burned [64]. Volunteer ginger plants, which can harbor *R. solanacearum*, should be removed as soon as they emerge, whether in ginger or other crops. If BW incidence is low, wilted ginger plants should be removed immediately to prevent contamination of healthy neighboring plants. These plants must be carefully destroyed in the same manner as ginger residues and sorted-out rhizomes. Additionally, rhizomes from neighboring diseased plants should not be used for planting [64].

Attention should be given to rouging and field sanitation, as these practices are crucial for maintaining rhizome quality in ginger production systems. Routine hygiene measures should include cleaning and disinfecting all farm equipment and storage rooms for harvested rhizomes. To prevent soil movement from an infested to a disease-free field, all tools and equipment must be decontaminated by washing with water and calcium hypochlorite (or other available bactericides) or sterilized by flame [64]. Machinery, vehicles, animal hooves used for traction, and personnel shoes from an infested field should be washed with water before entering another field. The flow of water from an infested field to adjacent fields must be avoided.

Weed control is also vital, as several weed species serve as hosts for *R. solanacearum* and can survive in the absence of a host crop [13]. Priou S, et al. [64] reported that *R. solanacearum* can survive in weeds, making it essential to weed fields before planting ginger or any other crop in rotation. Weeds can promote the survival of *Ralstonia* in the soil, transmit the pathogen to the next crop, and reduce the effectiveness of rotation practices.

Mulching and Bio-Mulching

Crop residue and plant leaf mulching in organically grown ginger beds are common adaptive practices among farmers in developing countries under rainfed conditions (Yuliar *et al.*, 2015). Locally available vegetable and aromatic plant residues used as mulch include chili (*Capsicum annuum*) [42], Chinese gall (*Rhus chinensis*), wood wax tree (*Toxicodendron xylosteoides*) [43], clove (*Syzygium aromaticum*) [44], cole (*Brassica* sp.) [45], eggplant (*Solanum melongena*) [46], eucalyptus (*Eucalyptus globulus*), lemon grass (*Cymbopogon citratus*), guava (*Psidium guajava* and *P. quinense*) [47], neem (*Azadirachta indica*) [48], pigeon pea (*Cajanus cajan*), and thyme (*Thymus* spp.) [29]. Additionally, forest trees such as oak and chir pine, local grasses (e.g., *Chrysopogon fulvus*, *Cymbopogon distans*, *Setaria glauca*, *Heteropogon contortus*), and shrubs (e.g., *Eupatorium odoratum*) possess antimicrobial properties that contribute to crop health [45].

These traditional mulching practices help reduce susceptibility to major ginger diseases such as bacterial wilt, soft rot, and leaf soft. Singh K, et al. [75] found that chir pine leaf mulching was particularly effective against bacterial wilt and soft rot compared to other bio-mulches. Chir pine leaf mulch also promoted sprout growth, reduced weed growth, and minimized bacterial wilt incidence [75]. Similar findings were reported in other studies [76].

In general, these adaptive practices help conserve and sustain soil moisture, minimize soil evaporation due to high solar radiation, optimize soil temperature, enhance seed germination, reduce soil erosion, and control weeds [77]. The resource-poor farmers, who may not have the means to purchase external inputs, have adapted these practices, resulting in significant improvements in soil and crop health and contributing to natural resource conservation.

Field Inspection and Quarantine Measures

During the ginger production period, fields are regularly inspected to detect early signs of diseases, especially quarantine diseases. Besides routine field inspections, identifying visual symptoms and conducting routine sampling for lab testing are crucial procedures [64]. According to **Liu S, et al.** [78], the success of quarantine procedures depends on employing rapid and sensitive detection techniques. Once bacterial wilt (BW) is introduced to an area, quarantine regulations must be enforced to prevent its spread to non-infested areas. Additionally, it is important to avoid transporting ware or seed rhizomes from infected areas to BW-free regions to prevent disease transmission. Although it is challenging to fully control all ginger trading, implementing these measures is one of the most effective preventative strategies available. Priou S, et al. [64] reported that quarantine measures can restrict ginger production and hinder the commercialization of ware ginger to BW-free countries or regions, impacting the economy of the affected areas. Therefore, because *Ralstonia solanacearum* is a significant quarantine pathogen transmitted through soil, water, and plant material, it is essential to detect it rapidly at the field level to halt its spread before significant losses occur.

Integrated Disease Management

In the integrated management of bacterial wilt, it is crucial to consider factors such as the pathogen's race and biovar [79]. Identifying the pathogen's distribution area is also important to prevent its occurrence and limit its spread to new regions. Effective management requires the implementation of integrated disease management methods that include cultural controls such as rotating with non-host crops, applying soil amendments, utilizing fallow periods, employing anaerobic flooding, using disease-free planting material, and selecting resistant cultivars [64]. According to Yuliar et al. [55], integrated disease management has been shown to reduce bacterial wilt disease incidence by 20-100% in field and laboratory conditions. Elphinstone J [13] reported that the most effective way to control the disease is by preventing its introduction into production areas through stringent quarantine and phyto-sanitary measures. Combining cultural practices, such as integrating crop rotation with resistant cultivars or using soil amendments, or combining organic matter with non-pesticide chemicals like formaldehyde or bleaching powder, has been effective in reducing bacterial wilt incidence and improving crop yield. Additionally, biological and chemical soil treatments can contribute to disease management, but they require the use of healthy, tested planting material and adherence to strict crop and storage hygiene practices.

Conclusion

Ginger is a vital spice and medicinal plant in Ethiopia, supporting many smallholder farmers and contributing significantly to the country's economy through exports. The crop is predominantly grown in the south and southwest of Ethiopia. However, production has been severely impacted by a bacterial wilt epidemic caused by *Ralstonia solanacearum*, which emerged in 2012. Bacterial wilt is a major constraint in tropical and subtropical regions, with the pathogen affecting a wide range of crops. It survives in soil, infected rhizomes, and plant debris, and can spread through irrigation water, soil, farm equipment, and weeds. The disease thrives in high soil moisture and temperatures between 30-35°C, but not in cooler conditions. Effective management of bacterial wilt requires preventive measures and a combination of agronomic and cultural controls. These include maintaining disease-free environments, using healthy seeds, soil and rhizome solarization, organic soil amendments, crop rotation, bio-fumigation, and proper field sanitation. Techniques such as timely nutrient application and removal of volunteer plants are also crucial. Implementing these methods helps in controlling the disease and sustaining ginger production.

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