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Review Article

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

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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. Furthermore, the use of organic matter such as crop residue and animal manure has been investigated as a means of inducing *R. solanacearum* suppression since it enhances the physical, chemical, and biological characteristics of soil. 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 disease 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

1. 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

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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 [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 [6, 8].

Bacterial wilt (*Ralstonia solanacearum*) is a major hinderance to the production of edible ginger (*Z. officinale* R.) in many tropical and subtropical regions of the world [6]. The disease is brought on by the soil-borne bacterial pathogen *R. solanacearum* race 4, which has severely harmed the edible ginger sector`s bottom line [9]. The *R. solanacearum* race 4 biovar 3 strains is the causal agent for ginger bacterial wilt in Ethiopia [8]. According to [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 cases of bacterial wilt syndrome on ginger were documented in 2012 from the Bench Maji Zone Bebeka coffee estate farm. The disease quickly spread to the nearby zone Sheka and resulted in a 67% yield loss [6]. Since its first report, the outputs of ginger production from major growing areas have significantly declined, and the volume delivered to the central market has 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.

The bacterial wilt of ginger is a highly devastating disease that is widespread in many regions. The disease is easily transferred by 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]. To combat and suppress this disease, however, a number of control methods were developed, such as host-plant resistance, agronomic and cultural control techniques, biological control, and chemical control [13]. To this end, the objective of this paper is to review the agronomic practices on ginger bacterial wilt disease management.

2. Literature Review

2.1. Causes and Symptoms of Ginger Bacterial Wilt

The disease is caused by *Ralstonia solanacearum* race 4 [9], although various races have also been reported. [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. Spots of wetness or straight lines show up on the collar area. The marginal tint of the lowest leaves, which progressively advances higher, turns yellow to bronze after these symptoms [6, 15]. At later stages, the leaves become flaccid with an 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 the advanced stage, the *pseudostem* appears slimy and dries out very rapidly, within 5 to 10 days [6]. The plants that are infested by the disease stand persistently and do not collapse. In the early stages of infection, the ginger rhizome shows grayish-brown discoloration. The rhizome becomes soft, water-soaked, and rotten; when it is pressed and immersed in clean water, a milky bacterial exudate oozes out [6, 15, 16].

Figure 1*. Symptom of ginger bacterial wilt diseases, A) Diseased shoots, B) Water soaked spots on leaves, C) Rotted rhizome. Source: Habetewold et al. [6].*

2.2. 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 [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. A greater prevalence, severity, and dissemination of the disease are caused by increased rainfall from July to September, which makes it easier for active inoculum to spread to surrounding fields through rain runoff and agricultural operations [17]. However, after October, moisture, temperature, and wilt incidence dramatically decrease. 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 (Figure 2).

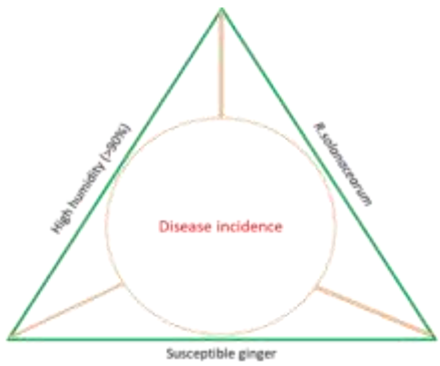

Figure 2. *Disease triangle for the incidence of ginger bacterial wilt disease.*

2.3. Agronomic Management of Ginger Bacterial Wilt

Bacterial wilt is a major problem and a production constraint for ginger and other vegetable crops [18]. Because of its broad host range, genetic heterogeneity, intricate epidemiology, and multiple mechanisms of transmission, bacterial wilt is challenging to manage [12, 19]. Various agronomic practices as control measures have been reported to combat this disease, such as selection of healthy seed rhizomes and fields, selection of resistant varieties, 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 [19] and [20]. Some of these agronomic and cultural control methods are discussed in detail below.

2.3.1. Seed Rhizome Treatment

Heat and solarization

As was previously mentioned, one of the main sources of inoculum for field infection is contaminated planting material. A technique called "rhizome solarization" has been developed to treat bacterial wilt by disinfecting rhizomes using solar light [20]. This technique is considered one of the most eco-friendly and energy-efficient methods available for rhizome treatment. According to [21], the ginger rhizomes that were heated for 30 minutes at 50℃ were free of *R. solanacearum*. Solar radiation raises the temperature of rhizomes, particularly in the vascular region [22]. The in-situ pathogen killing in the seed rhizome helps plants arising from solarized rhizomes frequently avoid disease [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]. Generally, rhizome solarization for two hours is enough to reach the necessary temperature inside the vascular tissue that the pathogen inhabits [20]. 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 application of non-saturated hot air is a promising method for disinfecting ginger seed rhizomes. According to [21], exposing ginger seed pieces to hot air at 75% relative humidity (RH) until their internal temperature reaches 50℃ 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. [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. [23] reported that soaking ginger seed in hot water at 50℃ 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]. Numerous studies have shown that applying heat to pathogens can eliminate them without affecting the seed rhizome's viability [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.

2.3.2. 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]. There is a long history of using soil solarization before planting to manage pests and soil-borne diseases in a variety of crops, such as peanuts, potatoes, ginger, onions, and carrots [18]. Plant growth, quality, and yield are improved for several years by the intricate biological, physical, and chemical changes brought about by solarization [25]. The majority of plant pests and diseases are mesophiles, meaning they cannot withstand high temperatures for extended periods of time and do not generate heat-resistant spores [26]. This makes soil solarization an effective method. According to [18], polyethylene is an appropriate covering for solarization since it transmits the germicidal components of sunshine. Another study found that 28 days of soil solarization with white plastic mulches before planting ginger greatly decreased the occurrence of bacterial wilt [27].

Soil bio-fumigation

The agronomic technique known as "bio-fumigation" suppresses soil-borne plant diseases by utilizing volatile compounds generated from plant leftovers [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 with promising results [28]. [29] reported that certain essential oils, including thymol, reduce tomato bacterial wilt incidence and *Ralstonia solanacearum* population density 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 biofumigants has been explored as part of an integrated disease management system for bacterial wilt.

According to [32], soil biofumigation using cabbage reduces the bacterial wilt disease incidence and also enhances the germination and yield of ginger rhizomes (Table 1). Additionally, [33] reported that solarization and soil biofumigation together greatly decreased the occurrence of bacterial wilt. [34] 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 biofumigants 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 and exhibited a good result (Table 2). 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.

Table 1. *Effect of soil bio-fumigation on germination, bacterial wilt disease incidence and rhizome yield of ginger.*

Treatments	Germination (%)	Mean Disease Incidence (%)	Rhizome yield (t ha^{-1})
T1	92.35	5.92	15.16
T2	87.03	8.23	13.71
T3	91.56	9.41	12.80
T4	86.72	8.54	12.42
T5	87.50	11.02	12.12
T6	85.63	22.11	7.70
SEm+	2.885	0.748	-
CD(at 5%)	8.695	2.254	-

T1 = Soil treatment by biofumigation using Cabbage*, T2= Soil treatment using bleaching powder @ 10g/bed (3m2), T3 = Rhizome solarization**, T4 = Rhizome treatment by rhizobacterial antagonist***, T5 = Rhizome treatment by endophytic bacterial antagonist****, T6 = Absolute control. Source: Bandyopadhyay and Khalko [32].

Table 2. *Effect of different bio-fumigant plants on germination, bacterial wilt disease incidence and rhizome yield of ginger.*

Treatments	Mean Disease Incidence at 60 DAP (%)	Rhizome yield (t ha^{-1})
Citronella	55.4^{abc}	9.63^{bc}
Palmarosa	49.66^{c}	10.4^{b}
Mint	56.43^{ab}	8.96^{c}
Lemongrass	42.43^{d}	13.43^{a}
Chinese chive	53.23^{bc}	12.36^{a}
Control	61.13^{a}	7.06^{d}
LSD (5%)	6.63	1.31
CV(%)	6.87	7.01

Source: Merga and Shamil [35].

Organic amendments

Adding organic matter to soilless growth media and agricultural soils improves the soil's inherent ability to inhibit soil-borne diseases and supplies plant nutrients [36]. Increasing soil disease suppression with the addition of organic amendments, such as animal manures and industrial byproducts, is an established method [37]. Organic amendments directly impact plant health and crop productivity. As organic matter in the soil breaks down, natural chemicals with a range of inhibitory effects are released, which can limit the amount of nutrients available to pathogens and impact their viability and survival [37]. Moreover, it has been demonstrated that organic amendments increase the activity of bacteria that are hostile to infections [26]. The breakdown of organic matter releases carbon into the soil, which stimulates microbial activity and strengthens the competitive effects of the soil [37]. Additionally, frequent applications of organic resources, such as compost or manure, eventually increase competitors' access to substrate, which inhibits pathogen growth and infection rates in the rhizosphere [38]. [39] reported that the severity of bacterial wilt can be lessened and pathogen survival in the soil suppressed by supplementing topsoil with varying kinds and rates of organic amendments.

In another study, the incorporation of household compost was found to reduce bacterial wilt incidence and severity [26]. [40] 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. Animal dung has been shown in numerous studies to suppress plant diseases; however, only a small number of studies have specifically examined its ability to prevent bacterial wilt disease. [41] observed reduction of bacterial wilt in soils treated with farmyard and chicken manure. Other studies have shown that incorporating cow dung manure and pig slurry reduces bacterial wilt incidence and severity [34]. However, [42] 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 [36], plant-pathogen combinations, application rates, types and methods of amendments, and the organic matter's stage of decomposition all affect how successful organic matter is at suppressing plant pathogens.

Crop residue management

According to [43], disease outcomes from residue management, especially from keeping crop residues in place, might be contradictory. There is growing evidence that residue retention can increase soil levels of general suppression. This effect is associated with high microbial activity levels, which are reliant on significant soil organic matter (OM) input [43]. Several studies have reported that bacterial wilt can be suppressed by plant residues from various plant species. For instance, residues from chili (*Capsicum annuum*) [44], Chinese gall (*Rhus chinensis*), wood wax tree (*Toxicodendron xylosteoides*) [45], clove (*Syzygium aromaticum*) [46], cole (*Brassica* sp.) [47], eggplant (*Solanum melongena*) [48], eucalyptus (*Eucalyptus globulus*), lemon grass (*Cymbopogon citratus*), guava (*Psidium guajava* and *P. quinense*) [49], neem (*Azadirachta indica*) [50], pigeon pea (*Cajanus cajan*), thyme (*Thymus* spp.) [29], and worm killer (*Aristolochia bracteata*) [51] have all been shown to suppress bacterial wilt.

Numerous research works have shown that organic matter can effectively combat bacterial wilt in field and greenhouse conditions. [52] reported that the bacterial wilt was completely suppressed under greenhouse conditions by adding freshly cut aerial portions of both crotalaria (*Crotalaria juncea*) and pigeon pea (*Cajanus cajan*) at quantities of 20–30% and incubated for 30 days. [52] 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. [53] found that soils that preserve crop waste have higher populations of cellulolytic microbes. Residue retention also benefits cellulolytic *Trichoderma* species, many of which are hostile to plant diseases, as reported by [54]. [39] reported that total inhibition of *R. solanacearum* infection was seen in soils amended with 10% coco peat and 1% green compost, whereas the unamended control soil showed a disease severity of 43%. [55] also found that about 50% of tested cruciferous plant residues reduced *R. solanacearum* populations in the soil. Retaining infected residues, however, occasionally raises the pathogens' capacity to serve as an inoculum.

Cultivation and fertilization

In agro-ecosystems, timely and appropriate nutrient treatment is a crucial component of pest management [39]. Plant susceptibility or resistance to pathogen infections can be influenced by elements found in their cell walls. Among these elements, silicon is thought to be advantageous for both plants and higher animals [38]. [56] reported that the tomato bacterial wilt was less common when silicon and chitosan were applied together because it created resistance. Calcium (Ca) is another well-known nutrient that suppresses disease, as noted by [57]. [58] also observed that plants with higher calcium concentrations had less *R. solanacearum* in their populations and less bacterial wilt in their tomato stems. Additionally, there was a correlation between reduced disease severity and increased Ca uptake by plant shoots [58]. [59] reported that the bacterial wilt decreased by 29% and 50%, respectively, by applying NPK and NP fertilizers at a rate of 100 kg/ha for each fertilizer. In addition, the incidence of bacterial wilt in tomato plants was decreased by applying rock dust and commercial organic fertilizer together [60]. This study found that the addition of rock dust effectively reduced bacterial wilt by increasing the pH and calcium content of the soil.

Furthermore, effective management of the soil usually results in an improvement in the makeup and activity of the soil microbiota, which strengthens the soil's ability to regulate biological processes [42]. [61] found that a high dose of nitrogen applied as ammonia compounds to sandy soil was more effective in reducing bacterial wilt severity than nitrates. [41] reported that when farmyard manure was applied at a rate higher than 4%, it was shown to be most efficient in suppressing the occurrence of bacterial wilt in the amended soil (5–8%). Studies have also looked into the effectiveness of bio-organic fertilizers (BOFs) in the management of soil-borne plant diseases. [62] discovered that the application of BOF increased biomass production, reduced the incidence of wilt disease, and changed the composition of the microbial community. [63] similarly reported that applying BOF significantly reduced disease incidence and *R. solanacearum* populations under both greenhouse and field conditions. However, occasionally, the addition of organic matter can have unfavorable outcomes like short-term oxygen depletion, pathogen stimulation, denitrification, and nitrogen immobilization [64]. 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.

2.3.3. 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 [65]. [66] 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 [66]. 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 [66]. Additionally, cucurbitaceous crops (pumpkin, cucumber, and 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 tomatoes by approximately 60%, likely due to its root exudates that inhibit pathogen infection [67]. This crop is now being used in our country to control ginger bacterial wilt. *R. solanacearum* can endure up to 161 days in soil [68]. The time required for elimination 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

Severe disease frequently arises from planting seed rhizomes that have been harvested from previously infected locations [18]. This emphasizes how crucial it is to use pathogen-free seed rhizomes in order to control disease occurrences. In the absence of efficient chemical and biological control techniques, planting healthy seed rhizomes in pathogen-free soil is the most effective way to prevent bacterial wilt outbreaks [69]. However, healthy seed rhizomes are not always readily available to all farmers due to the scarcity of planting material during peak planting time, particularly for crops like ginger, which require more than one ton of seed rhizomes per hectare.

Selection of disease free field

Site selection is crucial for effective management of ginger bacterial wilt disease. Ginger grown in soil free of bacterial wilt has been shown to provide healthy crops in most cases, as long as the seed rhizomes are uninfected [18]. According to [69], ginger is traditionally grown on virgin forest soil, previously fallowed soil, or on perennial crop plantations with a long following period. Ginger crops that are grown after such a long crop rotation are frequently healthy. Ginger can also be planted in social amenity forests with controlled shade or beneath perennial trees [69]. On the other hand, using sensitive techniques like polymerase chain reaction (PCR), soil can be analyzed for the presence of the pathogen [18]. It is now routine practice to detect the pathogen in soil using methods like PCR and double antibody sandwich enzyme-linked immunosorbent assay (DAS-ELISA) [18, 66].

Cover crops

Agriculture makes extensive use of cover crops, which come in a variety of types. According to [43], green manure crops are the most popular kind; they are cultivated with the intention of returning them to the soil to improve its levels of nutrients and organic matter (OM). When it comes to their effects on soil biota, cover crops are comparable to rotation crops, residue retention, or organic additions. They release ammonia into the soil and give soil biota more substrate and niche diversity [43]. Still, on their own, cover crops deserve to be regarded as an important method for managing soil health. [70] reported the application of green manure crops to control green bean diseases. Although closely related plants differed greatly in their efficacy as cover crop species, this suggests that OM inputs were not the exclusive cause of the effect. As demonstrated by certain legumes and brassicas, green manure crops frequently exhibit biofumigant qualities in addition to promoting microbial activity [43]. Currently, lemon grass and Chinese chive are being used as cover crop bio-fumigants to manage ginger bacterial wilt in our country (Figure 3).

Figure 3. *Lemongrass (top) and Chinese chive (bottom) bio-fumigants 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 microflora [43]. Tillage may have an impact on soil aggregation, which could lead to a decrease in bacterial biomass and diversity [71]. [66] reported that exposing plowed soil to summer heat in very warm areas also decreases soil infestation by *R. solanacearum*. Additionally, [72] noted that tillage generally results in less severe root rots produced by *R. solani* than direct drilling, and this effect has been utilized as a disease management method. There is currently no evidence that tillage has any influence on other elements of the soil biota; instead, it appears to directly affect the pathogen. Since various tillage techniques are frequently confused with other crop management strategies, assessing the impact of tillage on soil receptivity or suppressiveness is difficult [43]. Tillage and residue management effects are frequently combined when comparing "conventional" farming to organic, low-input, or conservation tillage systems. To determine the precise impact of tillage alone on the biological suppression of soil-borne diseases, more research is required.

Selection of resistant varieties

Plant resistance is one of the most effective methods for controlling bacterial wilt (BW). According to [57], the most affordable, eco-friendly, and successful way of disease control is seen to be employing cultivars resistant to bacterial wilt. But the main focus of resistance breeding has been on highly profitable crops including tobacco, tomato, potato, eggplant, pepper, and peanuts. This is because resistance breeding is guided by a number of variables [73]. These variables include the diversity and accessibility of sources of resistance, the genetic connections between resistance and other agronomic qualities, the mechanisms underlying interactions between plants and pathogens, the variability and differentiation of pathogenic strains, and breeding techniques [13]. According to [74], no resistance sources to *Ralstonia*-induced bacterial wilt have been identified within the *Zingiber* genus. This is attributed to a lack of genetic variation among accessions for disease resistance, which is a significant genetic improvement barrier for ginger.

Since ginger is an obligatory asexual crop, resistance breeding is restricted to germplasm screening, as reported by [75]. 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) [74]. Notably, [76] 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 [74]. However, [57] noted that resistance to bacterial wilt in many crops is often negatively correlated with yield and quality. As such, resistance cultivars might not be well-liked by farmers or consumers as a result of other agronomic characteristics. It is anticipated that in order to increase production and create resistant cultivars that are effective, future breeding efforts would concentrate on boosting bacterial wilt resistance through biotechnology methods.

Field and farm tools sanitation, and weeding

In order to reduce disease survival and spread, crop sanitation and cultivation practices are used. Ginger plant residues infected with bacterial wilt (BW) should be burned or removed from the field and buried underground and away from irrigation ditches [66]. 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 contaminating nearby healthy plants. These plants must be carefully destroyed in the same manner as ginger residues and sorted-out rhizomes. Additionally, rhizomes from nearby infected plants should not be utilized as a planting material [66].

Rouging and field cleaning are important techniques that must be followed to ensure the quality of the rhizomes in ginger production systems. All farm equipment, as well as the storage areas for collected rhizomes, should be cleaned and disinfected as part of routine hygiene procedures. All instruments and equipment must be decontaminated by washing with water and calcium hypochlorite or sterilized by flame in order to prevent soil movement from an infested to a disease-free field [66]. When moving from one infected field to another, equipment, cars, traction-using animal hooves, and worker shoes should all be cleaned with water. It is imperative to prevent water from spreading from an infected field to nearby fields.

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]. [66] reported that *R. solanacearum* can survive in weeds, making it essential to weed fields before planting ginger or any other crop in rotation. In addition to spreading the disease to the following crop and decreasing the efficiency of rotation procedures, weeds can help *Ralstonia* survive in the soil.

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 [57]. Locally available vegetable and aromatic plant residues used as mulch include chili (*Capsicum annuum*) [44], Chinese gall (*Rhus chinensis*), wood wax tree (*Toxicodendron xylosteoides*) [45], clove (*Syzygium aromaticum*) [46], cole (*Brassica* sp.) [47], eggplant (*Solanum melongena*) [48], eucalyptus (*Eucalyptus globulus*), lemon grass (*Cymbopogon citratus*), guava (*Psidium guajava* and *P. quinense*) [49], neem (*Azadirachta indica*) [50], 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 [47].

These traditional mulching practices help reduce susceptibility to major ginger diseases such as bacterial wilt, soft rot, and leaf soft. [77] 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 [77]. Similar findings were reported in other studies [78].

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 [79]. 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 [66]. The use of quick and accurate detection methods is essential to the success of quarantine protocols [80]. Following the introduction of bacterial wilt (BW), quarantine laws must be followed to prevent the disease's spread to uninfested 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. However, the implementation of quarantine measures may limit the production of ginger and impede its sale to nations or regions that are free of bacterial wilt [66]. This could have an adverse effect on the economies of the affected areas. Therefore, because *Ralstonia solanacearum* is a significant quarantine pathogen transmitted through soil, moisture, and seed, it is needed to detect it rapidly at the field level to halt its spread before significant losses occur.

2.3.4. Integrated Disease Management

In the integrated management of bacterial wilt, it is crucial to consider factors such as the pathogen's race and biovar [81]. Identifying the pathogen's distribution area is also important to prevent its occurrence and limit its spread to new regions. The application of integrated disease management techniques is necessary for effective management. These techniques include cultural controls such as the use of fallow periods, soil amendments, rotating with non-host crops, anaerobic flooding, disease-free planting material, and resistant cultivar selection [66]. According to [5, 57, 82, 83], integrated disease management has been shown to reduce bacterial wilt disease incidence by 20-100% in field and laboratory conditions (Tables 3, 4, and 5). By enforcing strict quarantine and phytosanitary regulations, the disease can be controlled most effectively when it is kept out of production areas [13]. 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. Furthermore, the management of diseases can be aided by biological and chemical soil treatments; however, their application necessitates the use of healthy, tested seed rhizomes as well as careful adherence to cleanliness protocols for crops and storage.

***Table 3**. Effect of integrated disease management on incidence of ginger bacterial wilt disease and rhizome yield of ginger at Teppi.*

Treatments	Mean Disease Incidence (%)		Rhizome yield (t ha^{-1})
	At 45 DAP	At 150 DAP	
Control	14.49[a]	79.76[a]	7.7[f]
Lemon grass (LG)	6.48[f]	48.74[g]	11.7[d]
Fertilizer (F)	9.64[cd]	64.47[d]	11.4[d]
Soil Solarization (SS)	15.30[a]	77.87[a]	8.6[e]
LG + F	7.88[ef]	64.48[d]	13.5[c]
LG + SS	10.00[c]	52.15[f]	13.2[c]
F + SS	9.60[cd]	64.46[d]	11.5[d]
LG + F + SS	7.40[ef]	45.85[h]	16.0[a]
LSD(5%)	1.02		0.59
CV(%)	7.84		3.2

Source: Guji *et al*. [5].

***Table 4**. Effect of integrated disease management on incidence of ginger bacterial wilt disease and rhizome yield of ginger in Bench-Sheko Zone, Southwestern Ethiopia*.

Treatments	Mean Disease Incidence (%)		Rhizome yield (t ha^{-1})
	At 45 DAP	At 165 DAP	
T1	28.33[a]	95.56[a]	5.00[e]
T2	18.33[b]	84.44[b]	9.29[d]
T3	15.00[bc]	79.44[b]	9.75[d]
T4	10.56[c]	47.22[d]	12.18[bc]
T5	1.11[d]	35.00[e]	15.09[a]
T6	9.44[c]	58.33[c]	13.01[b]
T7	11.67[bc]	62.22[c]	11.56[c]
LSD(5%)	7.44	9.27	1.12
CV(%)	31.01	7.89	5.84

T1 = (control), T2 = (hot water + bio-fumigation), T3 = (hot water + bio-fumigation + soil solarization), T4 = (seed socking and soil-drenching with Mancozeb + bio-fumigation), T5 = (seed socking and soil drenching with Mancozeb + bio-fumigation + soil-solarization), T6 = (seed and soil treatment with bleaching powder + bio-fumigation), T7 = (seed and soil treatment with bleaching powder + bio-fumigation + soil-solarization).
Source: Eyob and Desalegn (2022) [82].

Table 5. Effect of soil bio-fumigation on germination, bacterial wilt disease incidence and rhizome yield of ginger.

Treatments	Mean Disease Incidence (%)		Rhizome yield (t ha^{-1})
	At 45 DAP	At 165 DAP	
T1	18.33^{b}	84.44^{b}	9.29^{d}
T2	15.00^{bc}	79.44^{b}	9.75^{d}
T3	10.56^{c}	47.22^{d}	12.18^{bc}
T4	1.11^{d}	35.00^{e}	15.09^{a}
T5	9.44^{c}	58.33^{c}	13.01^{b}
T6	11.67^{bc}	62.22^{c}	11.56^{c}
T7	28.33^{a}	95.56^{a}	5.00^{e}
LSD(5%)	7.44	9.27	1.12
CV(%)	31.01	7.89	5.84

T1 = Soil treatment by biofumigation using Cabbage*, T2= Soil treatment using bleaching powder @ 10g/bed ($3m^2$), T3 = Rhizome solarization**, T4 = Rhizome treatment by rhizobacterial antagonist***, T5 = Rhizome treatment by endophytic bacterial antagonist****, T6 = Absolute control.
Source: Eyob [83].

3. 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 ℃, 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 volunteer plant eradication are also crucial. Implementing these methods helps in controlling the disease and sustaining ginger production.

Author Contributions

Behailu Mekonnen Abayneh is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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