BATTLING BACTERIAL WILT IN BRINJAL: INSIGHTS INTO PATHOBIOLOGY SYMPTOMS AND EFFECTIVE CONTROL MEASURES

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ABSTRACT

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Brinjal (*Solanum melongena* L.), belonging to the family Solanaceae, is an important vegetable worldwide, including in Bangladesh. Bacterial wilt, caused by *Ralstonia solanacearum* in solanaceous crop, including brinjal, is a devastating disease in humid tropics. It is the most destructive soil-borne plant pathogen with globaly distributed , having an unusually wide host range. Although the pathogen can attack more than 450 plant species belonging to 54 different botanical families, solanaceous crops are considered the most susceptible hosts. The pathogen can enter the plants through wounds or natural openings and cause rapid and fatal wilting symptoms, blocking the plant xylem system. The bacteria can cause secondary infections and severely damage the entire field, leading to a 30-70% yield loss depending on the cultivar, weather factors, soil type, cropping pattern, and bacterial strains. However, the effectiveness of conventional management against bacterial wilt is still limited, as the bacteria have several special features. The paper focuses on an overview of the pathobiological features of the bacterial wilt pathogen, disease symptoms, disease diagnosis, and management practices in brinjal.

Keywords: *Ralstonia solanacearum*, nutritional value, taxonomic position, biological control

INTRODUCTION

Brinjal (*Solanum melongena* L.) is the third most important vegetable in Asia and holds considerable significance in the Mediterranean belt (Alam and Salimullah 2021). It is grown year-round in Bangladesh. However, sustainable brinjal production is greatly hampered by various diseases every year, with damping-off, bacterial wilt and Phomopsis fruit rot being the most important (Singh *et al*. 2014, Pagoch *et al*. 2015). Among plant diseases, soil-borne infections account for 10–20% of yearly yield losses (Manda *et al*. 2020). Bacterial wilt disease, caused by *Ralstonia solanacearum*, is the most destructive soil-borne disease in temperate, subtropical and tropical regions (Yuliar *et al*. 2015). Also known as 'green wilt' disease, bacterial wilt causes the leaves of infested plants to remain green when wilting symptoms appear (Jiang *et al*. 2017). The bacterium was first described in potatoes, tomatoes, and brinjals in 1896 (Smith 1896) and later in tobacco in 1908 (Smith 1908). This bacterium typically invades plant roots from the soil through wounds or natural openings, then colonizes the intercellular space of the root cortex and vascular parenchyma (Genin 2010). Eventually, the pathogen enters the xylem vessel, spreading into the stem and leaves and blocking the translocation of water and nutrients (Yuliar *et al*. 2015). Consequently, wilt starts in the upper leaves, followed by complete plant loss within a few days (Nahar *et al*. 2019). Due to bacterial wilt, growers may lose around 30% of brinjal plants before fruit-bearing and up to 50-70% at the end of the season (Nahar *et al*. 2019). Another study reported a crop loss of 11.67–96.67% worldwide (Bainsla *et al*. 2016). Therefore, bacterial wilt is a serious concern for vegetable farmers.

The bacterium has a wide host range and can attack more than 450 plant species belonging to 54 different botanical families and has an extensive host range (over 200 species) (Karim and Hossain 2018, Wicker *et al*. 2007). The bacterium is considered as the second most ruinous pathogen among the ten most fatal bacterial species affecting economically significant yieldloses (Mansfield *et al*. 2012). The remarkable ability of the bacteria to remain in the soil for several years and tu form latent infections within native weeds makes it difficult to eradicate this destructive bacterium using conventional control methods. Additionally, most preventive methods and chemical controls are ineffective against this bacterium, antibiotics show little effect, and efficacious biocontrol methods have yet to be developed (Karim and Hossain 2018). Sometimes, growers may confuse this bacterial wilt with physiological or fungal wilt, despite fundamental differences (Figure 1). This often leads growers to implement improper management of the disease. Therefore, the manuscript has been parepared to focus on pathobiological features of the bacterial wilt pathogen, disease symptoms, disease diagnosis and management practices in brinjal.

Nutritional value of Brinjal

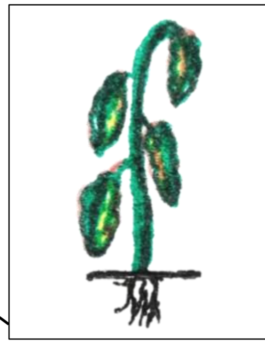
Brinjal is a rich source of abundant nutrients essential for proper health. It is ranked among the top ten vegetables that provide healthy food with low calories, containing high phenolic contents that aid in radical absorbing capacity. Brinjal supplies 25 calories per serving with no fat (Chadha and Kalloo 1993, Quamruzzaman *et al*. 2020). Brinjal comprises a complete set of minerals, vitamins, fibers, proteins, antioxidants, and some phytochemicals with scavenging activities (Table 1) (Noda *et al*. 2000, Whitaker and Stommel 2003). The fiber in brinjal aids digestion by removing toxins from the stomach, reducing the chance of stomach and colon cancer (Fraikue 2016). It is enriched with magnesium, manganese, potassium, and copper, crucial for healthy bones. Consumption of fresh fruits strengthens bones, controls diabetes, prevents paralysis, and is helpful in teeth-related problems. The fruit is also essential in treating different disorders such as asthma, dysentery, high blood pressure, and can also help cure osteoporosis, arthritis, diabetes, bronchitis, and heart diseases. Dry brinjal has been found beneficial in treating stomach bloating, gas, and piles. Extraction of roots and leaves of brinjal is used to cure skin diseases, cough, otitis, anorexia, toothache, burns, acts as a general stimulant, and treats piles, inflammation, intestinal foot pain, throat and stomach difficulties for ages (Quamruzzaman *et al*. 2020). It is a rich source of anthocyanin compounds, which play a significant role in diabetes, neuronal problems, cardiovascular disorders, and cancer. Purple brinjal, in particular, has a high amount of the nasunin compound in its flesh. Consumption of such purple eggplant helps against lipid peroxidation and ROS accumulation, which occur due to a high level of iron in cells (Casati *et al*. 2016, Noda *et al*. 2000).

Taxonomic position of *Ralstonia solanacearum*

According to some researchers, T.J. Burrill was the first to isolate this bacterium in 1890, but E.F. Smith was the first to publish a scientific description, classifying it in the genus *Bacillus* as *B. solanacearum* in 1896 (Smith 1896, Smith 1908, Kelman 1953). The pathogen underwent classification into several genera before being placed in the genus *Ralstonia*. It was initially in the genus *Bacillus*, then moved to the genera *Bacterium* and Pseudomonas, named as *P. solanacearum*. Additionally, it was temporarily placed in the genera *Phytomonas* and *Xanthomonas* (Kelman 1953) and in 1992, it was assigned to the genus *Burkholderia* (Yabuuchi *et al*. 1992). Finally, through phylogenetic and polyphasic phenotypic analyses in 1995, it was accommodated in the genus *Ralstonia* (Yabuuchi *et al*. 1995).

The genus *Ralstonia* was named in honor of the bacteriologist Ericka Ralston, who demonstrated a relationship between *Pseudomonas pickettii* and *Pseudomonas solanacearum* based on DNA homology (Ralston *et al*. 1973). Since then, it has been classified in the β-subdivision of the Proteobacteria, family Ralstoniaceae, genus *Ralstonia*, and is known as *R. solanacearum* (Stackebrandt *et al*. 1988).

Physiological Wilt
- Wilting occurs due to insufficient water in plant body
- Absence of any pathogen and ooze in cut sample
- The healthy state can be regained if proper management is taken before permanent wilting.



Wilted Plant

Fungal Wilt
- Fungus are present in isolated samples.
- Symptoms start from the base
- Absence of ooze in cut sample
- The healthy state can't be regained.

Bacterial Wilt
- Bacteria are present in isolated samples
- Symptoms start from young emerging buds. Yellowing of leaves followed by wilting.
- Ooze can be seen on exposed cut plant parts
- The healthy state can't be regained.

Figure 1. Differences among physiological, fungal and bacterial wilt

Table 1. Types and amount of nutrient present in Brinjal

Nutrients	Amount	Reference
Energy	33.6 Kcal / cup	Quamruzzaman *et al.* 2020
Carbohydrate	8.29 g/cup	
Protein	0.85-1.54%	
Fiber	2.4g/cup	
Phosphorus	14.4 mg/ cup	
Magnesium	10.6mg/ cup	
Manganese	0.25-0.41 mg /100 gm	
Potassium	117mg/cup	
Folate	13.4/ cup	
Vitamin A	1%	Naeem and Ugur 2019
Vitamin B complex	3-6%	
Ascorbic acid	3%	
Vitamin E	2%	
Vitamin K	3%	

Inoculum sources and environmental factors driving bacterial wilt infection

Sources of inoculum of *R. solanacearum* include infected plant materials (seeds, plants, tubers, etc.), infected debris, alternate hosts and weeds, infested soil, irrigation water, and farm equipment. Even plant parts with no visible symptoms can be inoculum sources because bacteria can remain latent in the host (Karim and Hossain *et al*. 2018). Dispersal of *R. solanacearum* occurs through various methods, among which environmental factors are the fundamental drivers (Manda *et al*. 2020). Vegetative propagating materials can spread the pathogen to significant distances, where they can remain latent for 2-10 years, acting as a reservoir of inoculum (Coutinho 2005). Weeds, infested wet soil, contaminated water, farm equipment, crop processing industry waste, tubers, and seeds pose a high risk of harbouring *R. solanacearum* (Van Elsas *et al*. 2001). Crop residues in fields and insects also serve as sources of inoculum (Wang and Lin 2005). Moreover, insects have even been considered as vectors that can spread the bacterium (Tahat and Sijam 2010).

Environmental factors are mainly responsible for developing, spreading, and disseminating bacterial wilt. The favourable temperature for *R. solanacearum* strains from tropical areas worldwide is 35°C, whereas for strains occurring at higher altitudes in the tropics and in subtropical and temperate areas, it is 27°C (Eppo 2004). The minimum and maximum growth temperature values are 8-10°C and 37-39°C, respectively (Kelman 1953). No growth has been observed at 4°C or 40°C (Eppo 2004). Regarding pH requirements, *R. solanacearum* growth is inhibited in acidic media, whereas positive growth is observed in alkaline conditions (Kelman 1953). No visible symptoms are observed below 16°C (Seneviratne 1988).

Inside and outside of the host: As a soil-borne pathogen, *R. solanacearum* can survive in various types of soils worldwide, allowing it to remain viable for a very long period, such as 2 to 10 years (Denny *et al*. 1994). Moreover, it can colonize non-host plants, including many weeds. After the wilting and death of the affected plant, the bacteria are found to be released into the soil. Adjacent plants can also be infected via root contact or the spread of the pathogen through irrigation water. It can enter through priming wounds and spread through contaminated water sources, symptom-less infected seedlings, and humans or machinery carrying infected soil (Figure 2) (Ramesh 2008).

The association of *R. solanacearum* with reservoir plants (host or non-host) or plant debris promotes the pathogen survival in soil and water and favours the overwintering of the bacteria in temperate regions. The bacteria invade the root xylem of tolerant hosts and weakly colonize at the stem level. There is an occasional presence of the pathogen in the root cortex or on the surface of non-host plants.

Bittersweet nightshade (*Solanum dulcamara*), a common perennial semi-aquatic weed, provides shelter to *R. solanacearum* cells and facilitates their continuous release into the water. The bacteria were reported to survive up to one year in agricultural soil even after treatment with an herbicide to eliminate the hosts. They were detected up to two years after crop removal and withstood a four-year intercropping period without losing wilting capacity, favoured by permissive temperature and moisture. Additionally, the bacteria could survive in aquatic environments and multiply without any nutrients (Álvarez *et al*. 2010).

The pathogens remain in the soil (especially in acidic soil), seeds, planting materials, weeds, and plant debris, acting as a primary source of inoculum. During invasion through roots, certain other soil-borne pathogens help with entry by causing injury to the roots of plants, especially the root-knot nematodes (*Meloidogyne* spp.) (Coutinho 2005, Johnson and Schaal 1952). Unwounded root infection is also possible when relatively large numbers of bacteria are available (Kelman and Sequeira 1965).

After entering, the bacteria colonize the intercellular space of the root cortex and vascular parenchyma (Genin 2010), eventually entering the xylem vessels and spreading into the stem and leaves (Yuliar *et al*. 2015). This blocks the translocation of water and nutrients, causing the plants to die. The bacterium can spread through irrigation water, rain splash, natural wounds in roots, root tips, root-to-root contact, nematode injury, and improper cultural operations (Choudhary *et al*. 2018, Kelman and Sequeira 1965). After destroying the host, it returns to the environment and survives in soil, water, or reservoir plants (Denny *et al*. 1994).

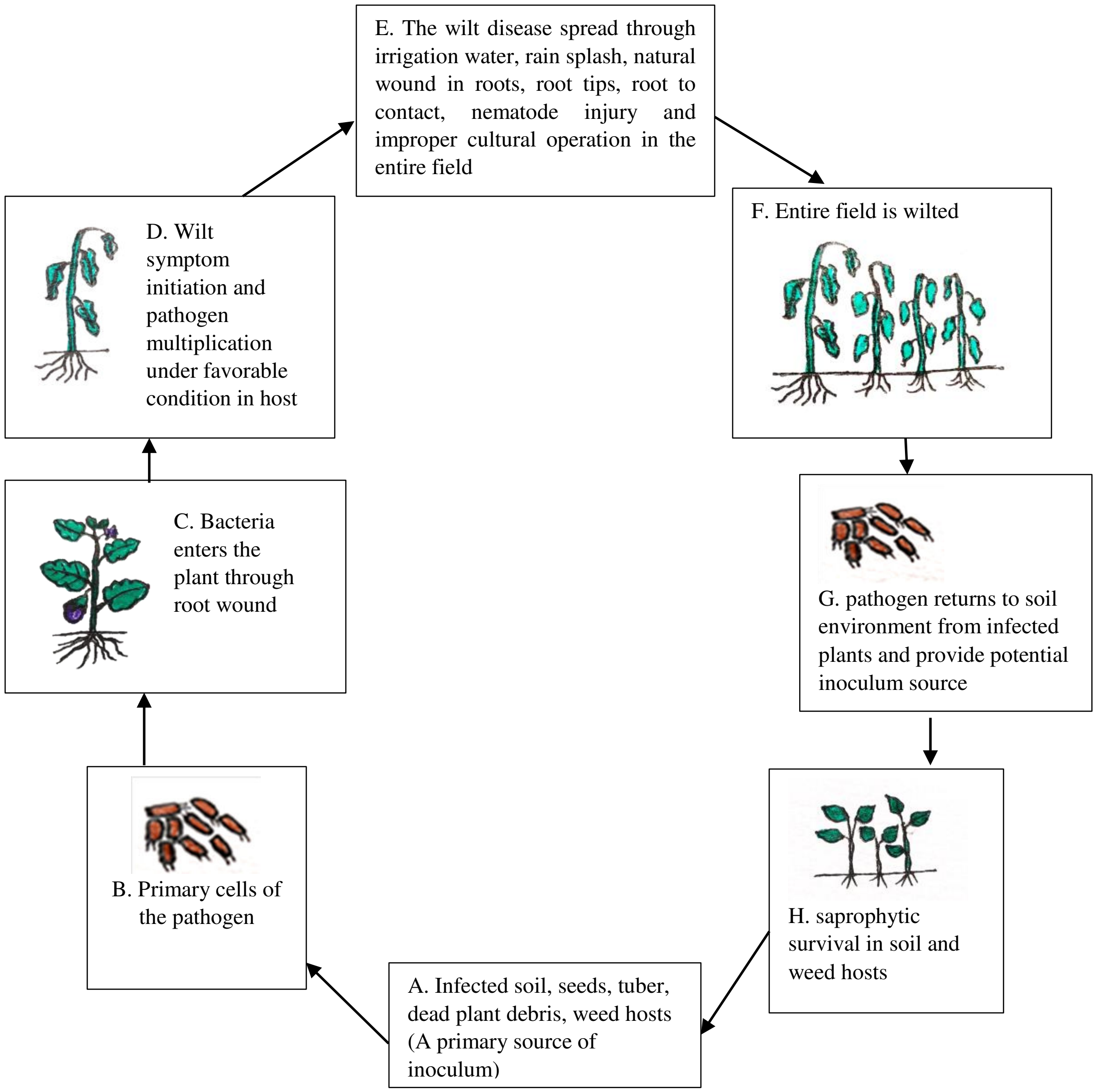


Figure 2. Disease Cycle of *Ralstonia solanacearum*

Host range of *Ralstonia solanacearum*

The pathogen has a worldwide distribution and a vast host range (Elphinstone 2005). The most important and widespread hosts are banana and plantain (*Musa paradisiaca*), brinjal (*Solanum melongena*), groundnut (*Arachis hypogaea*), *Heliconia spp*., potato (*Solanum tuberosum*), tobacco (*Nicotiana tabacum*) and tomato (*Lycopersicon esculentum*) (Eppo 2004). *R. solanacearum* strains have been classified into five races according to host range (Buddenhagen and Kelman 1964). Race 1 has the highest number of host species such as solanaceous crops- chilli and sweet pepper, eggplant, potato, tobacco and tomato; non-solanaceous crops: bean, groundnut and sunflower; ornamental plants like *Anthurium* spp., *Dahlia* spp., *Heliconia spp*., *Hibiscus* spp., *Lesianthus* spp., *Lilium* spp., palms, *Pothos* spp., *Strelitzia* spp., *Verbena* spp. and *Zinnia* spp.; trees like Eucalyptus and fruit trees as black sapote, custard apple and neem (Elphinstone,2005). The bacterial wilt of brinjal, caused by *R. solanacearum* in Bangladesh, mainly belongs to Biovar III and Race 1 (Rahman *et al*. 2013). Race 2 generally infects cooking, dessert bananas, plantain, and other *Musa spp*. and wild and ornamental

Heliconia spp. This race occurs mainly in tropical South America and the Philippines (Elphinstone 2005, EPPO/CABI 2006). Race 3 infects *Capsicum* spp., brinjal, geranium, potato and tomato, and weeds like *Solanum dulcamara* and *S. nigrum*. The race is widespread in all the five continents (Elphinstone 2005, EPPO/CABI 2006). Race 4 infects ginger and is limited in Asia and Race 5 is only limited to China (Elphinstone 2005).

Diagnostic Symptoms of *Ralstonia solanacearum*

Plants infected with *R. solanacearum* generally show symptoms externally and internally a few days after infection. The disease develops rapidly in warm weather and during heavy monsoons when the fields become frequently waterlogged (Das and Chattopadhyay 1955). The symptoms are characterized by sudden wilting and yellowing of the leaves, followed by undersized growth and eventually, the death of the plants (Figure 3) (Smith 1920). In the early stages of the disease, the first symptoms are generally seen on the young foliage of plants during the hottest part of the day (Elphinstone 2005). The plants recover soon when the temperature cools down, an identifying characteristic of bacterial wilt in the early stages of plants. The entire field can wilt under waterlogged or unfavourable conditions, and plants eventually dry (Manda *et al*. 2020). Stunting of the plants in the field at any stage is another symptom. Other symptoms of this disease include the bending of leaves downward, showing leaf epinasty (Smith 1920), adventitious roots growing in the stems, and the observation of narrow dark stripes corresponding to the infected vascular bundles beneath the epidermis, which is the most frequent external symptom (Smith 1920, Kelman 1953). Slimy viscous ooze typically appears on transverse-sectioned stems while keeping the stem in undisturbed clear water (Smith 1896), which is the most common sign of bacterial wilt and proves the presence of a bacterial cell mass in the xylem vessel. However, plants that do not show symptoms may remain hidden and infected for a longer period, which is a latent infection, that may lead the plant into expressing all the mentioned symptoms or none of them, even under conditions that are favorable for the bacteria (Harveson *et al*. 2015).

The first step for early diagnosis of bacterial wilt of brinjal is identifying disease symptoms in the field through a screening test (Liao 2005), which is easier than laboratory methods. Infected plants can be screened for bacterial wilt infection via the ooze test by placing the cut stem portion of the infested plant in sterile water. Specific tests, such as immune strips, can be used for rapid identification in the field (Manda *et al*. 2020). Other screening methods include the sick plot method (Hussain *et al*. 2005), and artificial inoculation (Artal *et al*. 2013). Unfortunately, it is not easy to identify the biovar or race of the bacteria through a screening test (Jiang *et al*. 2017).

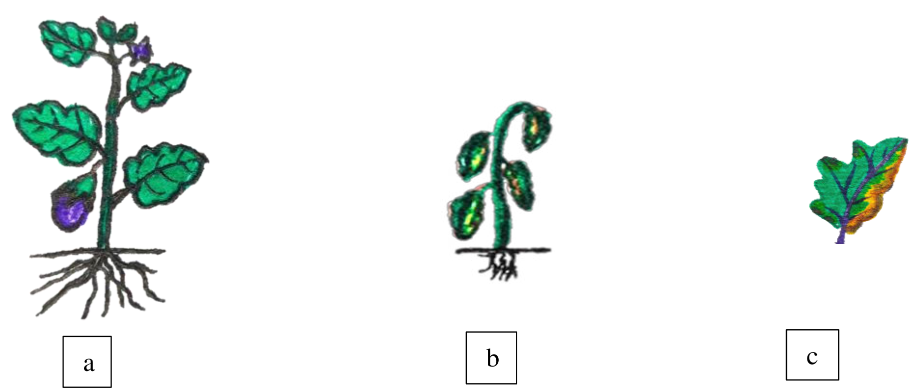


Figure 3. Pictorial view of healthy brinjal plants and wilted brinjal plant. (a) A healthy plant, (b) A wilted plant, (c) An infected leaf

Accurate disease identification in symptomatic or asymptomatic plants requires microbiological and molecular techniques (Pradhanang *et al*. 2005), which are time-consuming. To differentiate biovars, a biochemical growth test is performed with different strains based on the utilization of single alcohols (mannitol, sorbitol, and dulcitol) and disaccharides (sucrose, lactose, and maltose) (He *et al*. 1983). DNA probe hybridization and a fluorogenic polymerase chain reaction (TaqMan PCR) assay with a specific probe-primer set are being used for the proper assessment of the identification of strains of *R. solanacearum* (Weller *et al*. 2000). Determining the race is troublesome as *R. solanacearum* strains have a wide range of hosts (Manda *et al*. 2020).

Management Practices for Bacterial Wilt

Broad appropriation and long saprophytic tolerance make controlling bacterial wilt more troublesome than most pathogens, mainly once it is established in the soil (Manda *et al*. 2020). Bacterial wilt control has been attempted through different strategies, which include preventive, cultural, physical, biological and chemical control measures (Kurabachew and Ayana 2017). However, no single technique has yet shown complete efficacy in controlling this disease (Manda *et al*. 2020). Hence, integrated crop management (ICM) strategies and widely acceptable disease-resistant varieties will benefit farmers in the fight against bacterial wilt.

Cultural control measures: Cultural control includes cultivating methods that help improve the quality and quantity of crop yield and reduce the impact of the disease (Ajilogba and Babalola 2013). This includes quarantine, phytosanitary practices, disease-free certified seeds, disinfected equipment, controlled use of flood irrigation, and avoiding overhead irrigation. This measure is successful where the pathogen is not present previously (Karim and Hossain *et al*. 2018). According to Yuliar *et al.* (2015), using pathogen-free plant material is the most economical, environmentally friendly, and effective strategy for disease control. However, quarantine of pathogens can fail due to incomplete pathogen eradication, natural reinvasion, and reintroduction through short or long-distance movement of infected material from contaminated areas. Phytosanitary regulations should include certification with low or zero disease tolerances for this bacterium. During the early and later stages of the multiplication of basic planting material, hygiene is crucial to keep the materials pathogen-free (Janse and Wenneker 2002). Continuous cultivation of the same susceptible variety may establish a specific population of plant microorganisms in the soil. Crop rotation breaks this impact and results in the reduction of disease infestation by soil-borne microbes. The rotation of crops maintains soil structure and organic matter and reduces soil erosion (Janvier *et al*. 2007). Crop rotation with non-susceptible crops provides some control, but it is difficult as this bacterium has a wide host range (Kelman 1953). The invasion of bacterial wilt was delayed by 1 or 3 weeks, and wilt severity was reduced by 20–26% when a susceptible tomato variety (from the solanaceous family) was grown after corn, lady's fingers, cowpea, or resistant tomato (Adhikari and Basnyat 1998).

Combined amendment of rock dust and organic fertilizer in the soil reduced the incidence of bacterial wilt in tomatoes and might be effective against brinjal, too (Li and Dong 2013). Degradation of organic matter may influence the incidence of pathogens by releasing inhibitory substances in the soil, thus restricting nutrient availability (Bailey and Lazarovits 2003). Soil amendments contain bioactive molecules, such as growth regulators, toxins, and vitamins, which can influence microorganisms antagonistic to pathogens and maintain soil health. Different organic matter, such as plant residue (80%), animal waste (10%), and simple organic matter (10%), have been shown to control bacterial wilt disease in several trials. Animal waste also suppresses bacterial wilt disease; for example, applying pig slurry decreases the population of *R. solanacearum* in the soil (Yuliar *et al*. 2015).

Physical control measures: Various techniques for physical control have been created and demonstrated to be valuable for controlling *R. solanacearum*. These techniques include soil solarization, hot water treatment, and bio-fumigation, known as biological soil disinfection (Yuliar *et al*. 2015). Soil Solarization is executed by spreading a transparent plastic mulch sheet over the soil during high temperatures, helping to capture the sun's radiant energy, thus warming the soil layer. Consequently, insects, pathogens, weed seeds, weed seedlings, and nematodes are killed.

Solarization of the soil kills pathogens, improves the soil structure, and increases the availability of nitrogen and other essential plant nutrients (Ploeg and Stapleton 2001). It was reported that solarization of the soil reduced soil pH, potassium (K), sodium (Na), boron (B), and zinc contents, microbial biomass, and microbial respiration in soil but did not significantly affect other soil chemical properties (Yuliar *et al*. 2015). Hot water disinfection of the soil is usually implemented as a pre- and post-planting treatment. Hot water (70-90°C) can be poured on the soil before planting, raising soil temperature to deadly levels for weed seeds, insect pests, and phytopathogens. This method does not disturb soil microflora (Manda *et al*. 2020). Biological soil disinfection is an agronomic practice using volatile chemicals released from plant residues (Kirkegaard *et al*. 1996). The method typically involves four stages that include (I) flooding soil by irrigation, (ii) covering the soil with a plastic sheet to induce reduced soil conditions, (iii) introducing easily decomposable organic materials (e.g., rice straw, wheat bran, and rice bran) to the soil, and finally (iv) using the volatile chemicals released from plant residues (Manda *et al*. 2020, Runia and Molendijk 2010). Using a fumigant-type agrochemical in Japan has established a pathogen-free environment, which in turn helps produce higher-quality crops (Yuliar *et al*. 2015).

Use of resistant cultivars: The genetic route is one of the most favoured biotechnological applications against bacterial wilt. Genetically modified (GM) cultivars are disease-resistant and produce better-quality crops, greatly reducing the need for costly chemicals and making their production economically viable (Pandit *et al*. 2022). Using cultivars that are highly resistant to bacterial wilt is the most practical and environmentally friendly approach to dealing with bacterial wilt (Black *et al*. 2003). Genetic resources for bacterial wilt resistance in brinjal are available in the wild *S. torvum, S. sisymbriifolium*, and *S. khasianum*, which have a high degree of bacterial wilt resistance due to natural selection for survival (Rahman *et al*. 2002, Gousset *et al*. 2005, Raja and Rabindro 2017). The identified bacterial wilt-resistant wild relatives and other breeding lines can be used for resistance breeding against bacterial wilt.

Biological control: This method involves inhibiting one living entity by another (Sharma and Kumar 2000) and has developed as a promising and safe alternative to the use of chemicals, especially as an Integrated Pest Management (IPM), to reduce the utilization of fungicides (Whipps 2001). Recent studies have shown the potential of root-colonizing microorganisms to inhibit or displace soil-borne pathogens at the root-soil interface and thereby protect the root health of perennial and annual crops such as cotton, potato, tobacco, cucumber, wheat, peanut, banana, and rice (Anuratha and Gnanamanickam 1990). Several examinations revealed that biocontrol of bacterial wilt might be achieved by the proper utilization of antagonistic rhizobacteria and epiphytic bacteria, such as *Serratia marcescens, Bacillus subtilis, Bacillus cereus, Paenibacillus macerans, Bacillus pumilus, Pseudomonas fluorescens*, and *Pseudomonas putida* (Table 2) (Achari and Ramesh 2019, Alamer *et al*. 2020, Aliye *et al*. 2008, Kurabachew *et al*. 2007). The application of biocontrol agents along with organic fertilizer can be effectively incorporated into wilt disease management (Table 2). Mechanisms of biological control include multifaceted interactions among the host, pathogen, and antagonists regarding competition for survival (space and nutrients), mycoparasitism, plant-mediated systemic resistance, production of indole acetic acid, antibiotics, siderophore, and extracellular degrading enzyme production (Di Francesco *et al.* 2016, Sharma and Kumar 2000).

The benefits of using bio-control agents include self-sustainability, as they spread on their own after initial establishment, reduce the input of non-renewable resources, provide long-term disease suppression, and are environmentally friendly (Quimby *et al*. 2002, Whipps *et al*. 2007). The biggest obstacle to using bio-control agents is their poor performance due to inconsistent colonization, followed by difficulties associated with mass production, storage and formulation (Yuliar *et al*. 2015).

Table 2. Antagonistic microbial entities used to control bacterial wilt diseases in brinjal

SI.No.	Biocontrol agents	Effects and mechanisms	Reference
1	*Pseudomonas fluorescens (Pfcp)* + *Pseudomonas solanacearum*	Fluorescent bacteria were used in the field and greenhouse, which showed a 40% increase in the survival of brinjal plants by producing several antibiotics.	Anuratha and Gnanamanickam 1990
2	*Bacillus* sp. and *Pseudomonas mallei*	Induces synthesis of inhibitory compounds and production of siderophores and showed 81% success in brinjal.	Ramesh and Phadke 2012
3	*Bacillus amyloliquefaciens*	Antibacterial activity was induced due to lipopeptide, iturin and fengycin secreted by the antagonistic bacteria, controlling brinjal bacterial wilt with 25.3% efficacy if used alone.	Alamer *et al.* 2020, Chen *et. al.* 2014
4	*Bacillus amyloliquefaciens* + organic fertilizer	Controlled brinjal bacterial wilt with 70.7% efficacy because organic fertilizers improve the survival of the antagonistic bacteria in the soil.	Chen *et al.* 2014
5	*Pseudomonas polymyxa*	Polymyxin and tridecaptin were produced and showed strong antagonistic activity.	Alamer *et al.* 2020
6	*Pseudomonas putida*	Produced xantholysin B and xantholysin C with antibacterial activity against Gram-negative bacteria.	Alamer *et al.* 2020
7	*Pseudomonas fluorescens*	Suppresses plant pathogens by producing antibiotics such as 2, 4-diacetylphloroglucinol (DAPG), pyrrolnitrin pyoluteorin, and phenazine-1-carboxylate.	Ramesh *et al.* 2009
8	*Bacillus cereus*	Colonizes rhizosphere and endophytic tissues of brinjal, which can play an important role in suppression of *R. solanacearum*	Achari and Ramesh 2019

Grafting onto resistant rootstock: The growth of susceptible plant cultivars grafted onto resistant rootstock is one of the most convenient systems for growing brinjal due to the lack of resistant genotypes with desirable agronomical traits and wide climatic adaptability (Collonnier *et al*. 2003, Kumbar *et al*. 2021). Rootstock breeding is a promising and emerging area where resistant sources or breeding rootstocks can resist pathogens across strains. The use of susceptible commercial cultivars grafted onto bacterial wilt-resistant rootstocks has been demonstrated to be an effective management tool in the Philippines and Bangladesh (Rahman *et al*. 2010). The grafting technique is also gaining popularity in Japan (65% of the total area), Turkey (10% of the total area), Korea, and Israel (Yassin and Hussen 2015). *Solanum torvum*, a wild relative of brinjal, is of great interest as a rootstock for grafting brinjal for its highly vigorous nature, complete graft compatibility with brinjal scions, and resistance to a wide range of soil pathogens (Rahman *et al*. 2002, Daunay 2008, Moncada *et al*. 2013). However, *S. torvum* exhibits a long germination period, poor germination percentage, and a short hypocotyl length, which might be a challenge for grafting (Ginoux and Laterrot 1991, Miceli *et al*. 2014). However, seed soaking, gibberellic acid, potassium nitrate treatments, and light irradiation positively stimulate germination (Barik *et al*. 2020). The use of *Solanum melongena* 'Haritha' as a rootstock shows maximum plant spread, the number of primary branches, and stem thickness even better than *S. torvum* in terms of yield, which may be due to the prevalence of the vigorous root system of the Haritha rootstock causing efficient absorption of water, minerals, and nutrients (Kumbar *et al*. 2021).

Chemical control: A limited number of chemicals are available to control bacterial wilt effectively (Grimault *et al*. 1994). However, none have been proven successful when applied alone because of the complex nature of *R. solanacearum*. The bacterium localizes inside the xylem and remains latent in the soil (Yuliar *et al*. 2015). Moreover, no known eradication bactericides are available for chemical control of bacterial wilt disease (Hartman 1994). Fungicides like benomyl, carbendazim, flubendazole, and propiconazole are sometimes broadly used in affected areas for controlling bacterial wilt (Manda *et al.* 2020). Fumigants, including meta-sodium, 1,3-dichloropropene, and chloropicrin, algicide 3-[3-indolyl] butanoic acid, and plant activators such as Valdoxylamine and validamycin A, have also been applied to manage bacterial wilt incidence (Manda *et al.* 2020). Antibiotic striazolothiadiazine and streptomycin sulfate, other chemicals such as bleaching powders, or weak acidic electrolyzed water have been shown to control *R. solanacearum* effectively. The combination of ASM and thymol significantly reduced disease incidence in tomato but not in all solanaceous crops (Yuliar *et al.* 2015). However, the application of synthetic substances to control *R. solanacearum* has been seriously questioned due to the high costs involved (Manda *et al.* 2020).

CONCLUSION

Bacterial wilt remains a significant obstacle in brinjal production and affects other solanaceous crops as well. Presently, no effective control measures exist against this bacterium due to its intricate nature, rapid adaptability in various environments, and broad host range. A comprehensive understanding of brinjal bacterial wilt and its management is crucial for the farming community to implement timely and suitable control measures. This knowledge can aid the scientific community in devising technically adapted, socially acceptable, farmer-friendly, and economically viable methods to combat this bacterium. An integrated management approach-incorporating cultural, physical, biological control, and chemical control may yield the best results in mitigating bacterial wilt damages to crops. However, resistance to bacterial wilt in many crops has often shown a negative correlation with yield and quality (agronomic traits). To address this, the development of a bacterial wilt-resistant brinjal cultivar can be achieved through biotechnological approaches.

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