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## A REVIEW ON SOLANACEOUS PLANT DISEASES CAUSED BY *RALSTONIA SOLANACEARUM* HAVING SERIOUS ECONOMIC IMPACT

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### ABSTRACT

The highly destructive soil-borne pathogen *Ralstonia solanacearum* (Smith) Yabuuchi *et al.* (*RS*) affects a variety of solanaceous plants and causes catastrophic diseases leading to massive economic losses across the globe. Biochemical assays separate this bacterium's strains into 5 races and 5 biovars by host range. This bacterium's race 1 biovar 1, which is endemic to the south-eastern United States, infects many different vegetable and ornamental species. Some solanaceous vegetables and ornamental crops are infected by *RS* race 3 biovar 2, which causes brown rot, bacterial wilt, and Moko disease. The race 3 biovar 3 is not hosted by tobacco. The most devastating *RS* diseases affect solanaceous crops like potatoes, tobacco, pepper, tomatoes, and eggplant. This review offers a thorough examination of this bacterium's impacts on solanaceous crops, emphasizing their economic impact. It also emphasizes the importance of integrated disease management, including current developments in control methods (biological, physical, chemical, cultural, and integrated) and bio-control effectiveness and suppression mechanisms, to combat deadly bacterial wilt diseases. Avirulent *RS*, *Pseudomonas*, *Bacillus*, and *Streptomyces* spp. strains are examples of well-known Biological Control Agents (BCAs). Research shows that plant waste, animal manure, and organic materials reduce bacterial wilt. It's crucial to incorporate pest management for bacterial wilt infections. This review also identifies intriguing possibilities for future study and collaboration on this bacterium. Understanding this bacterium's complexity and using effective management measures can lessen its detrimental effects on agriculture.

**Keywords :** *Ralstonia*, bacterial wilt, biovar, control measure, race, solanaceous crops.

### 1. Introduction

More than 50 distinct botanical families are represented among the more than 200 plant species that can serve as hosts for the fungus *Ralstonia solanacearum* (Smith) Yabuuchi *et al.* (*RS*) (Denny, 2006). This bacterium (*RS*) can survive in infected plants for a long period. Many asymptomatic weeds port the bacteria in their roots and the disease dominate in various soil types. The sources of inoculum for agricultural fields, covertly infected propagative plant material, and it is contaminated. Under high temperature and high moisture conditions, *RS* caused bacterial wilt in tomato plants amounts to a 30%–90% yield loss (Singh *et al.*, 2015). Through the root endodermis, the *RS* in tomatoes further colonizes the vascular parenchyma. Xylem dwelling *RS* releases a virulence factor, extracellular polysaccharides, that disturbing the xylem vessels, increase the viscosity of the xylem fluid, and hinder the water transport; making the plant succumb to bacterial wilt. It is interesting to note that the incidence of *RS* in field conditions decreased dramatically with the decrease in soil moisture content, which highlights the significance of soil and plant water levels in determining the severity and spread of the illness. In this study, they were reviewed the interaction between *RS* and different soil, therefore impact of the

combined stress on the plant. It also presented different instances of the interaction between low soil moisture and other major xylem-dwelling pathogens, such as *Xylella fastidiosa* (causes bacterial leaf scorch and Pierce's disease), *Xanthomonas campestris* (causes black rot and bacterial wilt), and tomato spotted wilt virus (causes tomato spotted wilt). The physiological and anatomical changes were also showed that are adopted by the tomato plants as well as potato that are resistant to drought or wilt. According to some reports, potato brown rot disease in many regions is mainly spread through irrigation with contaminated water. This bacterium may spread by colonizing the rhizospheres of non-host plants. High temperature (30–40 °C) promotes occurrence of this disease, but soil temperatures below 18 °C are not suitable for the bacterial wilt disease. There are many infection areas of *RS*, of which the common ones include innate infection on planting material, from soil, water, air, actions of insects and mechanical transmission. The bacterium can survive in soil, in which it survives for long periods of time and in irrigation (drainage) water. *RS* diagnostic techniques include bioassays, dilution plating on semi-selective media, fatty-acid analysis, immunofluorescence and PCR. The genetic and pathogenic behaviour, variations make the development of diagnostic and detection and control measures of *RS* more difficult and

complex. Although it is difficult to calculate the total economic losses caused by wilt disease, it ranks as one of the most serious plant diseases in the world. It is the second most damaging potato disease after late blight in tropical and subtropical areas. The pathogen attacks about 30 plant species both monocots and dicots, of which the most susceptible plants are potatoes, tomatoes, pepper, eggplant, and groundnut. This will assist in the management of these serious world-wide economic food losses particularly. In a taxonomic study of the genus *Pseudomonas* (Yabuuchi *et al.*, 1992), the genus *Burkholderia* was showed to encompass the variation found in this group and the name *Burkholderia solanacearum* was proposed. Subsequent study of this genus disclosed that *R. solanacearum* was sufficiently distinct from other members and proposed to the newly genus *Ralstonia* (Yabuuchi *et al.*, 1995). *RS* as a species has a highly wide host range, but different pathogenic species may show very limited host ranges. The race that is now prevalent in the EPPO region prefers a small range of hosts, particularly the weed *Solanum dulcamara* L., tomatoes, and potatoes. Over 200 species, especially tropical and subtropical crops, are susceptible to one or another of the races of *RS*. Worldwide, the most important are: banana, tomatoes, potatoes and tobacco. Some minor host crops are: groundnuts (*Arachis hypogaea* L.), *Anthurium* spp., rubber [*Hevea brasiliensis* (Willd. ex A. Juss.) Muell. Arg.], *Capsicum annuum* L., cotton (*Gossypium hirsutum* L.), castor beans (*Ricinus communis* L.), cassava (*Manihot esculenta* Crantz.), ginger (*Zingiber officinale* Rosc.), and eggplant (*Solanum melongena* L.). *RS* does not like as a single bacterium with a uniform biology and host range, but as a complex of variants, variously described as groups, races, biovars, biotypes, sub-races and strains. This bacterium is extremely polyphagous. It has a number of strains that vary mostly in how well they can break down different sugars and nitrates, as well as in the kind of hosts on which they may grow. The different classifications (Fig. 1) of *RS* have caused a different amount of perplexity in the study. However, following differentiated physiological races were recognized based on the hosts (Yabuuchi *et al.*, 1995).

- Race 1, with several strains isolated from various hosts and environments;
- Race 2, adapted to tropical triploid banana trees;
- Race 3, in temperate climates, prefers to attack the potato, tomato, and eggplant;
- Race 4 is linked to ginger; and
- Race 5 affects the mulberry tree.

Four biotypes (biovars) were identified by Hayward (1964) based on their capacity to synthesise acid from a variety of disaccharides and sugar alcohols. Mulberry strains have been showed as 4 *RS* biovar 5 (Buddenhagen, 1985). A restriction fragment length polymorphism (RFLP) analysis split races and biovars into two "main groups" (Cook and Sequeira, 1993). Race 1 strains from Asia (biovars 3, 4, and 5) grouped together, as did race 1 strain from the United States (biovars 1, 2, and 3). The fingerprinting experiments have shown Race 3 (biovar 2) to be extremely homogeneous. However, when studies of South American strains of race 3 (biovar 2) were made, more variation was seen: a) "normal" strains found east of the Andes watershed and throughout the world; b) strains that are biochemically distinct, up until now

only found west of the watershed of the Andes; and c) strains that behave almost as an intermediate between race 1 and 3 that are found in the lowlands of South America. These results, along with the discovery of resistance in wild *Solanum phureja* Juz. & Bukasov (Sequiera and Rowe, 1969), point to the potential origin of race 3. The bacteria are able to propagate both in the soil, where it can live for various amounts of time, and in the water used for irrigation. In tropical areas, many weeds have been shown to be alternate hosts. The weeds' resistance to infection is due to the bacterium's slow rate of development. Entry into plants is by way of stem wounds, injured roots, or through stomata. Within the plant, the bacteria move in the vascular bundles, a process which is swift by higher temperature. Speed of movement is also dependent on the plant part colonized, for instance in tobacco bacteria move accelerated in the roots (Ono *et al.*, 1984). This is followed by colonization of the xylem, where the bacteria adhere to invade the lumen or the vessel walls. Destroyed the vessels by bacteria is the major cause of wilting. The sickness is at its most dangerous between the temperatures of 24 and 35°C and is extremely uncommon in climates where the average temperature of any winter month is lower than 10 °C. There are distinct temperature requirements for maximum disease development and reproduction for the different races (biovars) (Swanepol, 1990). There is a correlation between prolonged periods of wet weather, high soil moisture, or rainy seasons and increased disease severity. Soil moisture is also one of the major factors affecting reproduction and survival of the pathogen; the most favourable soil moisture is -0.5 to -1 bar (Nesmith and Jenkins, 1985). A little bit unfavourable weather, such low temperatures, affects how symptoms manifest. In Kenya, when planted at lower altitudes it certified and obviously healthy potato seed tubers produced at altitudes of 1520-2120 m showed infection (Nyangeri *et al.*, 1984). This was due to a latent infection of the tubers grown in an environment less favourable to the pathogen.

## 2. DETECTION AND IDENTIFICATION:

### 2.1 Symptoms on the foliage & tubers of potatoes (*Solanum tuberosum* L.)

**On Foliage:** The first visible symptom is wilting of leaves at the ends of the branches; finally, plants fail to recover and die. At the time of development, the stem becomes streaky brown. Moreover, epinasty of the petioles may occur. A white, slimy mass of bacteria drops from vascular bundles which are broken or cut. This slime seeps off from potato stem as threads, when kept in a beaker with water.

**On Tubers:** Depending on how the disease develops, external signs are frequently not present. Additionally, symptoms could be mistaken for those of ring rot caused by *Clavibacter michiganensis* subsp. *sepedonicus*. The bacterial slime that frequently exudes from the eyes and stem-end connection of infected tubers is a telltale sign of *RS*, which can be differentiated from other types of rot by itself. When the sick tuber is cut, the vascular ring will reveal browning and necrosis. A mass of yellowish disintegrated vascular tissue and bacterial slime must be squeezed out of the tuber in the event of ring rot, whereas plants with foliar symptoms brought on by *RS* have both healthy and diseased tubers.

## 2.2 Symptoms on tomatoes (*Lycopersicon esculentum* Mill.)

If environmental conditions are good for the infection, the plant as a whole may quickly begin to wilt. The youngest leaves are the first to be harmed and have an appearance of sagging, particularly during the hottest part of the day. According to McCarter (1991), the vascular tissues of the stem have a brown tint, and if the stem is cut lengthwise, it is possible to see drips of a white or yellowish bacterial slime. When environmental conditions are less favourable, the illness progresses more slowly, causing the stem to become stunted and producing a significant number of adventitious roots.

## 2.3 Symptoms on tobacco (*Nicotiana tabacum* L.)

According to Echandi (1991), in extreme situations, stem-attached leaves wilt but do not change colour. Unilateral wilting and early leaf yellowing on one side of the plant, or even only a portion of a leaf, are two of the key signs. When cut open, the vascular tissues exhibit the same dark color as tomato. The major and secondary roots turn from brown to black.

## 2.4 Symptoms on bananas (*Musa balbisiana* Colla)

Moko disease, which is brought on by *RS*, is frequently mistaken for the illness brought on by *Fusarium oxysporum* f. sp. *cubense*. On young and growing plants, the young leaves become a pale-green or yellow and collapse. When fruits are affected, a clear distinction is possible - a brown and dry rot in the case of Moko disease. Within a week all leaves may collapse. Young suckers may be stunted or twisted blackened. The pseudo stems show brown vascular discolouration (Hayward, 1983).

## 3. CONTROL MEASURES

### 3.1 Chemical methods (pesticides and non-pesticides)

The majority of all uses are for herbicides, followed by insecticides and fungicides. The use of pesticides has been crucial for controlling plant diseases. The use of pesticides increased by 1.8% per hectare for every 1% increase in agricultural yield, according to Schreinemachers *et al.* (2012). This is notably true with herbicides and fungicides or bactericides, which have generally increased more than proportionally with crop output per hectare. To suppress bacterial wilt, many pesticides have been employed, including algicides (3-[3-indolyl] butanoic acid), fumigants (1,3-dichloropropene, chloropicrin), and plant activators that cause systemic resistance in tomato plants (validamycin-A and validoxylamine). Methyl bromide, 1,3-dichloropropene, or metam sodium added to chloropicrin dramatically boosted tobacco and tomato yields while reducing bacterial wilt in the field from 72% to 100%. However, this hasn't always been the case. Edwards-Jones (2008) claimed that pesticides provided more net benefits than alternative control measures. For instance, if farmers use pesticides improperly or irresponsibly, some of the pesticide may be released into the environment (Gadeva and Dimitrow 2008), contaminate soil and/or groundwater (Acero *et al.*, 2008), and be hazardous to farmers (Dasgupta *et al.*, 2007). Bactericides such as triazolothiadiazine (0.5 to 12 mM, in solution) (Khanum *et al.*, 2005), streptomycin sulphate (400 mg kg<sup>-1</sup> of soil) (Lin *et al.*, 2010), as well as other chemicals like bleaching powders (application rate to the field, 30 kg ha<sup>-1</sup>) as sterilisers (Sharma

and Kumar, 2000) are destroy the microbes. It has been suggested that acibenzolar-S-methyl (ASM) causes systemic resistance (Hacisalihoglu *et al.*, 2007). While ASM and thymol alone had no effect, the two together dramatically decreased the prevalence of illness and enhanced tomato yield (Hong *et al.*, 2011). Through the induction of resistance, silicon or Si (Dannon and Wydra, 2004), and chitosan (Kirkegaard *et al.*, 1996) decreased the prevalence of bacterial wilt. According to Wang *et al.*, increases in soil microbial population and enzyme activity (urease and acid phosphatase) were linked to Si-mediated resistance. It has been discovered in the past that soaking seeds in a solution of low sodium chloride increases the vigour and resistance of tomato seedlings against *RS* (Nakaune *et al.*, 2012). It is believed that either generated systemic resistance or antibacterial activity is responsible for the non-pesticide compounds' ability to prevent bacterial wilt. There have been some innovative techniques reported to stop bacterial wilt. Live pathogen microbial cells were either captured using coated sawdust containing 10 g kg<sup>-1</sup> of 1% N-benzyl-4-vinylpyridinium chloride and styrene (Kawabata *et al.*, 2005) or coagulated in soil containing 10 mg kg<sup>-1</sup> of a co-polymer of methyl methacrylate with N-benzyl-4-vinylpyridinium chloride at a molar ratio of 3:1 (Kawabata *et al.*, 2005). Phosphoric acid solution's bacteriostatic effects stopped the spread of the bacterial wilt pathogen (Norman *et al.*, 2006). As they have less detrimental effects on the environment, a variety of non-pesticide chemicals have the potential to be used in the field to manage the bacterial wilt disease; nonetheless, economic factors frequently determine the chemicals used. Only important crops that risk suffering noteworthy economic losses in the absence of treatments are capable of withstanding the cost of expensive pesticides and frequent applications. A diagnosis based on economic thresholds is very crucial for deciding if chemical treatments are required because crop output and quality are unaffected by low disease severity or in the absence of pathogens.

### 3.2 Biological methods

#### 3.2.1 Biological Control Agents (BCAs)

Now-a-days, concerns about the widespread use of the harmful chemicals are making biological control more popular. The benefits of BCAs include the possibility of self-sufficiency, the ability to spread on their own after the original implementation, a decrease in the use of non-renewable resources, and the long-term control of disease in an environmentally friendly way. BCAs use interactions to keep their processes going. These interactions include competition for food and space, antibiosis, parasitism, and the induction of systemic resistance (Agrios, 2005). Montesinos (2003) explains that bacteria make up most of the BCAs that have been trademarked. Biocontrol agents for bacterial wilt can be talked about in the following heads: isolating, testing, and identifying BCAs; using BCAs; making BCAs better; stopping BCAs from spreading; and the effects of BCAs on the environment. Studies revealed some promising BCAs, mostly avirulent strains of *R. solanacearum* and *Pseudomonas* spp., *Bacillus* spp., *Streptomyces* spp., and other species, showed that they might be able to stop bacterial wilt. Recently, 109 different strains of endophytic or rhizobacterial bacteria were studied to see how well they killed *RS* bacteria. Twenty-two isolates of *Pseudomonas* spp. and *Bacillus* spp. were found to be effective (Ramesh and Phadke, 2012). Kurabachew *et al.*

(2013) looked at 13 out of 150 types of rhizobacteria based on in vitro antibiosis. Among them were *Pseudomonas* spp., *Serratia marcescens*, and *Bacillus cereus*. Rhizospheres of healthy plants are often used to separate rhizobacteria that help plants grow. This process has been explained in an exciting way. Huang *et al.* (2013) found that isolates from the rhizosphere of sick plants were better at preventing disease than those from healthy plants. They found that the antagonists' biocontrol efficacies were linked to root colonization abilities, but not to antibiosis in vitro. This suggests that root colonization capacity may be a key factor in disease control. *Acinetobacter* species (Xue *et al.*, 2009), *B. pyrrocinia* (Nion and Toyata, 2008), *Burkholderia nodosa*, *B. tericola*, *B. sacchari*, *Chryseobacterium daecheongense* (Huang *et al.*, 2013), bacteriophages (Alvarez *et al.*, 2007), *Bacillus thuringiensis* (Zhou *et al.*, 2008), and *Chryseobacterium indologenes* are a few unique or uncommon BCAs that have been reported to control bacterial wilt disease. The Competition induced systemic resistance, antibiosis, and the development of enzymes that breakdown the cell wall and siderophores are potential suppression methods for these species. There have been reports of some fungal BCAs controlling bacterial wilt. Following the inoculation of *Glomus versiforme* in pot cultures, populations of *RS* in the rhizosphere, on root surfaces, and in the xylem of tomato plants reduced by 26.7, 79.3, and 81.7%, respectively. Both *R. solanacearum* and *G. versiforme* colonised plants, increasing the amount of soluble phenols and cell-wall bound phenols in the root tissue, which may be connected to the fungus's ISR (Zhu and Yao, 2004). *Pythium oligandrum*, a different fungus, may be able to control the bacterial wilt disease, where cell wall proteins may be crucial in the development of resistance to *RS* and the activation of the ethylene-dependent signalling system (Hase *et al.*, 2006). In vitro growth of this bacterium was discovered to be inhibited by an antibiotic component present in shiitake mycelia leachate. In addition, the lichen *Parmotrema tinctorum* (Gomes *et al.*, 2003) and three endomycorrhizal fungi (*Gigaspora margarita*, *Glomus mosseae*, and *Scutellospora sp.*) have been recognised as BCAs against *RS* (Tahat *et al.*, 2012). BCAs have disadvantages as well. Poor performance due to sporadic colonization is the biggest issue. BCAs only suppress a specific pathogen or disease in some host plants. BCA development, storage, and use have also been problematic. Spore former BCAs can solve storage issues.

### 3.2.2 Organic matter

Organic soil amendments significantly affect plant and agricultural productivity. They improve soil's physical, chemical, and biological properties, helping plants to develop. Organic matter breakdown in soil can directly affect pathogen's viability and survivality by restricting nutrients and releasing naturally existing inhibitory compounds. By releasing carbon during organic material degradation, soil microbes improve competition effects (Bailey and Lazarovits, 2003). Organic soil amendments improve the activity of disease-fighting microorganisms. Vitamins, growth regulators, and poisons in organic inputs may affect soil bacteria. Youssef and Tartoura (2013) found that compost treatment increased the enzymes ascorbate peroxidase, monodehydroascorbate reductase, dehydroascorbate reductase, and glutathione reductase,

which increased plant's resistance against bacterial wilt pathogen.

Organic matter is made up of recently living organisms and decomposes or results from decomposition. It is divided into simple organic carbons and carbons with plant or animal origins. Different organic matter, including plant residue (80%), animal waste (10%), and simple organic matter (10%), were proven to manage the bacterial wilt illness in prior references to an *RS* study. According to Larkin, biological additions were typically successful at introducing microorganisms to natural soil, and depending on the specific kinds, quantities, and combinations of organisms supplied, this had a variety of consequences on the soil microbial communities. A novel strategy involves controlling bacterial wilt in an organic hydroponic system using a rhizosphere biofilm that only develops on organic system roots (Fujiwara *et al.*, 2012).

#### 3.2.2.1 Plant residue controlling bacterial wilt

Previous studies claimed that plant residues from various plants, such as chilli (*Capsicum annum* L.) (Teixeira, 2006), Chinese gall (*Rhus chinensis* Mill.) (Yuan *et al.*, 2012), clove (*Syzygium aromaticum* L.) (Amorim *et al.*, 2011), cole (*Brassica* sp. L.) (Arthy *et al.*, 2005), eggplant (Almeida *et al.*, 2007), eucalyptus (*Eucalyptus globulus* Labill.) (Paret *et al.*, 2010), geranium (*Geranium carolinianum* L.) (Ooshiro *et al.*, 2004), guava (*Psidium guajava* L.) (Acharya *et al.*, 2009). The primary proposed modes of action for the plant residues are antibacterial activity, followed by indirect pathogen suppression via enhanced physical, chemical, and biological soil qualities. For instance, the antibacterial substances from *Tagetes patula* L. were identified as 5-(3-buten-1-ynyl)-2, 2'-bithienyl and 5-(4-acetoxy-1-butynyl)-2, 2'-bithienyl, which both reduced *R. solanacearum* in an in vitro experiment (Terblanche and Villiers, 1998). Other plants, such *Cryptomeria japonica* D. Don, generated sandaracopimarinol and ferruginol, and *Cyphomandra betacea* (Cav.) Sendtn. had a glycosidase inhibitory protein that, in an in vitro experiment, prevented *R. solanacearum* from growing. When used at a density of 100 mg kg<sup>-1</sup>, lansiumamide B isolated from the seeds of *Clausena lansium* (Lour.) Skeels inhibited tobacco bacterial wilt more effectively than the antibiotic streptomycin (Li *et al.*, 2014). Previous studies showed that organic matter might effectively combat bacterial wilt in greenhouses and on the open ground. In a greenhouse experiment, for instance, the freshly cut aerial parts of pigeon pea (*Cajanus cajan* L.) and crotalaria (*Crotalaria juncea* L.) were incorporated at concentrations of 20-30% and incubated for 30 days; but after inoculation they totally suppressed bacterial wilt of tomato for 45 days (Cardoso *et al.*, 2006). However, the application rate of this organic matter was high and, therefore, not practical for farmers. At an application rate of 0.72% in the field, thymol oil from a thyme plant reduced bacterial wilt by 65% in the fall 2002 tomato cultivation and by 82% in the fall 2003 tomato cultivation. According to Alfano *et al.* (2011), the disease-suppressing properties of compost made from olive waste appeared to be the result of a combination of suppression phenomena brought on by the presence of microorganisms that compete with one another for nutrients and space as well as by the activity of particular antagonistic microorganisms.

### 3.2.2.2 Animal waste controlling bacterial wilt

Few research works have demonstrated that animal waste lowers bacterial wilt disease, despite the fact that several have already indicated that animal waste manages plant disease. Although changes in bacterial community profiles have been hypothesised, the mechanisms underlying the increased reduction of this pathogen's population and the suppression of disease remain unknown. Another study hypothesised that higher microbial activity and larger concentrations of cultural bacteria and fungus were connected to the reduction of bacterial wilt by farmyard and poultry manure (Islam and Toyota, 2004). A lower illness index was found to be associated with the pathogen's poor survival in that investigation. However, there are drawbacks to the widespread usage of organic waste. According to the research by Janvier *et al.* (2007) the main determinants of how effectively organic matter suppresses plant pathogens are: i) the plant-pathogen interaction; (ii) the rate of treatment; (iii) the nature of amendment.

### 3.2.2.3 Simple organic compounds controlling bacterial wilt

The effects of common organic compounds, such as amino acids, sugars, and organic acids, on the progression of bacterial wilt in tomato plants have been investigated in pot studies. Lysine was added to the soil (2.5 mg/g) and a pumice culture media (0.25 mg/g) to minimise bacterial wilt in tomatoes by 85-100% (Igawa *et al.*, 2008) and 58-100% (Posas *et al.*, 2007), respectively. The suppression mechanism was not linked to the development of systemic resistance, but rather to changes in the makeup of the soil's microbial population, which caused the pathogen to die more quickly.

Riboflavin, on the other hand, caused a number of defensive reactions and secondary metabolism in cell suspensions, protecting tobacco against *RS* (Liu *et al.*, 2010). In tomato plants, DL, -3- aminobutyric acid (BABA) also enhanced polyphenol oxidase activity while decreasing catalase activity, which may have the effect of causing the tomato to develop a resistance to bacterial wilt. Further, potent bactericidal effects of Methyl gallate was also reported on *RS* (Hassan and Abo-Elyours, 2013).

### 3.2.3 Physical methods

*RS* Methyl gallate has been successfully controlled physically using a variety of techniques, including solarization and hot water treatments. According to Vinh *et al.* (2005) the incidence of bacterial wilt was decreased by soil solarization utilising transparent plastic mulches for 60 days before tomato planting. Baptista *et al.* (2006) investigated how soil solarization decreased tomato bacterial wilt. In contrast to other soil chemical characteristics, soil solarization dramatically decreased soil pH, potassium (K), sodium (Na), boron (B), and zinc concentrations as well as microbial biomass and microbial respiration. Before tomato plants were planted, the infected soil underwent a heat treatment at either 45°C for 2 days or a minimum temperature of 60°C for 2 hours. Before the use of soil solarization can be expanded, a number of factors need to be carefully taken into account, including the management of temperature, the release of volatile compounds, and the practical and/or economic viability in the field. Treatments using chilly temperatures can occasionally be as beneficial as those using

heat. Because of the cool weather, bacterial wilt rarely affects tobacco crops grown in May or June (winter crops) in north Queensland. However, the disease did appear when crops were planted in the spring (September to November), especially when bacterial wilt had previously occurred and crop rotation was not used. Reduced bacterial wilt and pre-incubation at lower temperatures (4°C) had a negative impact on the survival of this bacterium (Akiew *et al.*, 1993). Reduced bacterial wilt and pre-incubation at lower temperatures (4°C) had a negative impact on the survival of this bacterium which was found to survive for six months in an infected geranium at a constant temperature, but it dropped quickly in repeated cycles of two days at 5°C and two days at 10°C over the winter. The mechanism of action for the physical measures used to control bacterial wilt typically involves the high or low temperatures used to destroy microorganisms (Scherf *et al.*, 2010).

The agronomic approach known as "biofumigation," which involves employing volatile compounds emitted from plant residues to control soil-borne plant diseases, has recently come to the public's attention. The process of biofumigation is also known as biological soil disinfection (BSD), and pathogen suppression involves the creation of organic acids or heavy metal ions (Momma, 2008). The pathogen was inactivated by the use of a silver-coated non-woven fabric filter, a source of visible light (Bando *et al.*, 2008), or an electrostatic spore precipitator with ozone-saturated water (Zhou *et al.*, 2007).

### 3.2.4 Cultural practices

#### 3.2.4.1 Cultivar resistant

The most affordable, eco-friendly, and efficient way of disease control is the development of cultivars that are resistant to bacterial wilt. Links in the genetic code that connect resistance to other agronomic traits, differentiation and variability in pathogenic strains, the mechanism of plant-pathogen interactions, and breeding or selection practises have all been common influences on the development of bacterial wilt resistance in crops of broad economic importance, such as the tomato, potato, tobacco, eggplant, pepper, and peanut (Boshou, 2005). For instance, when the tomato cultivar Arabidopsis NPR1 (nonexpresser of PR genes) was added, 28 days after the inoculation, it increased bacterial wilt resistance and reduced the occurrence of wilt by around 70%. (Lin *et al.*, 2004). By electrically fusing mesophyll protoplasts, somatic hybrids of *Solanum melongena* cv. Dourga (Long white) and two varieties of *Solanum aethiopicum* L. (African eggplant or bitter tomato) were created and it was discovered that they were resistant to *R. solanacearum*. Before such genetically modified crops may be used commercially, public acceptance in Japan is required. According to Prior *et al.* (1996) resistant plants were severely invaded by *R. solanacearum* without exhibiting any signs of wilt. According to Nakaho *et al.* (2004), reduced pathogen transport from the protoxylem or primary xylem to other xylem tissues prevented bacteria from multiplying in the stems of resistant tomato plants. *RS* inoculated resistant and sensitive plants' cell walls were examined using a proteomic method to determine how certain molecules interacted with one another (Dahal *et al.*, 2010). In many crops, bacterial wilt resistance has typically been inversely associated with production and quality. Due to other agronomic features and the potential for poor release,

resistant cultivars may not be well-received by farmers or consumers. Further efforts to enhance crop productivity through genetically strengthening resistance to bacterial wilt utilising biotechnology technologies are expected in the future.

#### 3.2.4.2 Crop rotation, multi-cropping

Crop rotation has advantages such as maintaining soil organic matter and structure and reducing soil erosion, which is frequently brought on by continuous row crops. Crop rotation prevents the growth of particular plant pathogenic populations, but continuous cropping with the same susceptible host plant has the opposite effect and is frequently linked to a decline in plant illnesses brought on by soilborne pathogens (Janvier *et al.*, 2007). For instance, when a susceptible tomato variety was planted after corn, lady's fingers, cowpea, or resistant tomato, the beginning of bacterial wilt was postponed by 1 to 3 weeks and the severity of the disease was reduced by 20 to 26%. (Adhikary and Basnyat, 1998). While the production of potatoes was one to three times higher than that of monocultured potatoes, the incidence of wilt was reduced by 64 to 94% when potatoes were grown in rotation with wheat, sweet potatoes, maize, millet, carrots, sorghum, or phaseolus beans (Katafiire *et al.*, 2005). According to Yu (1999), in the study of multi-cropping the suppression mechanisms of Chinese chive (*Allium tuberosum* Roxb.), which decreased the incidence of bacterial wilt in the tomato by about 60%, most probably due to the Chinese chive's root exudates inhibit *RS* from infecting tomato plants.

#### 3.2.4.3 Soil amendment

Previous research showed that fertilizer use decreased the occurrence of bacterial wilt. The most well-known fertilizer for preventing disease is calcium. Increased calcium levels in plants lessened the severity of bacterial wilt and the quantity of *RS* in tomato stems. In addition, a rise in calcium uptake by tomato shoots was associated with a decline in disease severity (Yamazaki *et al.*, 2000). According to Lemaga *et al.*, the treatment of (N + P + K) and (N + P) (application rate of each fertilizer @ 100 kg ha<sup>-1</sup>) decreased bacterial wilt by 29% and 50%, respectively, and raised potato production to 18.8 t ha<sup>-1</sup> and 16.6 t ha<sup>-1</sup>, which was higher than that in untreated controls (11.2 t ha<sup>-1</sup>). According to Hacisalihoglu *et al.* (2007) bacterial wilt caused alterations in the way that nutrients, particularly Ca, B, and P, were distributed in tomato leaves. Li and Dong (2013) demonstrated that the addition of rock dust and synthetic organic fertilizer decreased the occurrence of bacterial wilt in tomatoes. The incidence of bacterial wilt in tomatoes was likewise significantly decreased by a single amendment with rock dust, and a greater soil pH and calcium content were important contributors to this reduction. Many components of cell walls affect how susceptible or resistant plants are to pathogen infections, and Si is thought to be a helpful component for both plants and higher animals. According to Kiirika *et al.* (2013), the use of Si and chitosan together increased resistance in the tomato, which decreased the occurrence of bacterial wilt. Si and chitosan both have additive effects on the illness.

#### 3.2.5 Integrated Pest Management (IPM)

The main objectives of an integrated plant disease control programme, also known as IPM, (Agrios, 2005) are: (i) to eliminate or reduce initial inoculums, (ii) to reduce the effectiveness of initial inocula, (iii) to increase the host's resistance, (iv) to delay the onset of disease, and (v) to slow down secondary cycles. However, IPM often combines two or three treatments, including cultural practises, chemical, and biological techniques, to reduce bacterial wilt disease by 20–100% in the field or in a lab setting. For instance, in soil contaminated with *RS*, the prevalence of bacterial wilt in tomatoes was observed after the addition of an organic mixture made up of industrial and agricultural waste, such as bagasse, rice husks, oyster shell powder, urea, potassium nitrate, calcium superphosphate, and mineral ash, or Actigard (active ingredient: acibenzolar-S-methyl (ASM)). When the organic mixture was added, the incidence of bacterial wilt in the tomato decreased by 32%, but Actigard only reduced it by 5%. In contrast, the incidence of bacterial wilt was reduced by 53% with the addition of the organic combination and Actigard (Anith *et al.*, 2004).

The relative relevance of the factors causing production losses must be assessed in order to create an IPM. Combinations of cultural practises, including crop rotation with a resistant cultivar or a soil amendment, or organic matter with a non-pesticide chemical like formaldehyde or bleaching powder, seem to have significantly decreased the frequency of bacterial wilt and enhanced crop production (Adhikari and Basnyat, 1998). When ASM and *Pseudomonas fluorescens* Pf2 were applied together, the incidence of bacterial wilt in tomatoes was significantly reduced. However, using ASM or *P. fluorescens* Pf2 alone had similar effects. A prior study found that the prevalence of bacterial wilt was decreased when resistant cultivars of the tomato were combined with endophytic bacteria (*Bacillus* sp. and *Serratia marcescens*, both of which displayed no antibiosis) (Barretti *et al.*, 2012). In IPM for soil-borne diseases, grafting is a key tactic. Grafting has been used to treat diseases caused by oomycete pathogens (*Phytophthora*), bacterial pathogens (especially *Ralstonia*), fungal pathogens (*Verticillium*, *Fusarium*, *Pyrenochaeta*, and *Monosporascus*), root knot nematodes, and several soil-borne viruses (Louws and Kubota, 2010). To prevent diseases and increase yields, we must use techniques that are simple, useful, profitable, and environmentally friendly (Fig. 2).

#### 4. Remarkable major research works done on the soil borne pathogen *R. solanacearum* till date

As methodology changed from phenotypic, biochemical, and molecular research to genomics and functional genomics, names were frequently changed. The bacterial wilt pathogen was divided into three species as a result of its variety, extensive host range, and geographic distribution, as revealed by genomic analysis of the phylogenetic relationships among strains. Table 1 provides a summary of the significant events and accomplishments that have taken place in relation to the bacterial wilt pathogen, *Ralstonia solanacearum* species complex (*RSSC*), as studied through an exhaustive literature survey.

**Table 1:** Major events in the history of the bacterial wilt pathogen, *R. solanacearum* species complex, as determined by taxonomic and phylogenetic analysis.

Sl. No.	Year	Major events
1.	1896	Described by Erwin Frank Smith as <i>Bacillus solanacearum</i>
2.	1898	Placed in the genus <i>Bacterium</i> by Chester
3.	1914	Placed in the genus <i>Pseudomonas</i>
4.	1923	Placed in the genus <i>Phytophthora</i>
5.	1939	Transferred to the genus <i>Xanthomonas</i>
6.	1948	Replaced into the genus <i>Pseudomonas</i>
7.	1962	Designation of 3 races
8.	1964	Designation of 4 biovars
9.	1989	Division into 4 RFLP groups
10.	1991	Use of 16S rRNA sequencing & tRNA PCA primers for differentiation
11.	1992	Transferred to the genus <i>Burkholderia</i>
12.	1995	Transferred to the genus <i>Ralstonia</i>
13.	2000	Use of PCR-RFLP & AFLP for diversity studies
14.	2002	First whole genome sequencing of <i>Ralstonia solanacearum</i> strain (GMI 1000) (Salanoubat <i>et al.</i> , 2002)
15.	2005	Phylotype based classification
16.	2006	Core genes & pathogenicity factors
17.	2010	Whole genome analysis of strains from 3 groups
18.	2012	Designation of 8 clades
19.	2013	Cluster analysis of orthologous genes
20.	2014	Proposal of 3 new species; The RSSC has a number of macromolecular secretion systems, such as type I secretion systems (T1SS), type II secretion systems (T2SS), type three secretion systems (T3SS), type four secretion systems (T4SS), and type six secretion systems (T6SS). Further, RSSC infection needs the <i>acrA</i> and <i>b</i> efflux genes in T1SS.
21.	2016	Confirmation of 3 new species
22.	2019	Effector repertoires, effector triggered immunity
23.	2020	Phylogenetic studies based on whole genomes
24.	2021	Genomic comparisons of two <i>R. solanacearum</i> strains showing divergent virulence against <i>Solanum pimpinellifolium</i> L. and <i>S. Americanum</i> Mill. led to the identification of the avirulence effectors RipJ and RipAZ1 (Moon <i>et al.</i> , 2021).
25.	2022	The RSSC contains a number of macromolecular secretion systems, such as type I secretion systems (T1SS), type II secretion systems (T2SS), type three secretion systems (T3SS), type four secretion systems (T4SS), and type six secretion systems (T6SS). It has been established that RSSC infection needs the <i>acrA/B</i> efflux genes in T1SS (Geng <i>et al.</i> 2022).

Biovar of *RS* wilt of tomato in Nigeria was surveyed by Adebayo and Ekpo (2005) and reported that the wilt disease caused by *RS* in tomato fields in the production area of Ogun State in June 1996. Ibadan's National Horticultural Research Institute found similar diseases. Terminal leaves wilted two days after irreversible wilt. For further study of the causal organism, 10 tomato plants showing wilt symptoms were selected from each of 5 vegetable fields at Ibadan. A creamy bacterial sap was extracted from these samples, cultured at 30 °C for 48 hours, and then plated on tetrazolium chloride media. For biovar determination colonies that were fluidal and white with pink canthers were used. Cultures were incubated at 30 °C for 29 days and monitored daily for colour changes. All 25 isolates of bacterial cells were inoculated individually to each of the six media. The basal media contained three hexose alcohols (dulcitol, mannitol), and three disaccharides (cellobiose, maltose, lactose). The 25 isolates were tested using 4-week-old seedlings each of eggplant cv. Black beauty, *Lycopersicon esculentum* cv. Ibadan local, *Capsicum annuum* cv. California wonder, *Solanum tuberosum* cv. Kufri. According to Messiha (2006) potato brown rot disease caused by *RS* race 3 biovar 2 (Phylovar II, sequevar 1), is a serious endemic disease in the Nile Delta of Egypt. In EU, it is a serious endemic disease, that's why export of potatoes from Egypt is restricted to pest-

free areas. The causal organism *RS* survived and suppressed depending on different soil types, its origin, and management. It has been shown that, the pathogen survived longer in Dutch than in Egyptian soils and in clayey soil than the sandy soils. Further, organic management reduced pathogen's survival in Egyptian soils but not affected in Dutch soils. Most soils benefited from NPK fertilisation and cow dung, while compost did not. Sandy Dutch soils grow disease like any other soil. Plant resistance increased with DOC (substrate availability) and decreased with soil potassium and calcium contents. While organic management increased in all Dutch soils the disease was slightly suppressed in organic compared to conventional sandy soils from Egypt. In organic Dutch soils it was related to a high DOC content.

Lemessa and Zeller (2007) reported that *RS* is a diverse species and it can be classified into distinct races based on its host reactivity and host range differences. In Ethiopian fields 62 strains collected from different hosts were pathogenically characterised by inoculating into five differential hosts (potato, eggplant, tomato, tobacco and pepper). In the other study, with race 3 and race 1 strain are randomly designed in the effect of plant age on susceptibility of different hosts. The research found that while each strain had a different effect on



pepper and tobacco, all of them rapidly wilt potato, tomato and aubergine. Based on tests for pathogenicity, race 1 was assigned to 19 strains, and race 3 to 43 strains. In Ethiopia raises concern, the presence of race 1 strains as a wider host range. The effect of plant age on wilt development specifically depends on the type of host and the race of the pathogen. Generally, plant age did not significantly affect wilt development in tomato, potato, and eggplant, while in pepper and tobacco plant significantly reduced wilt development, indicating the existence of age-related resistance against the pathogen.

According to Tahat and Sijam (2010), *RS* (race 3 biovar 2) is a causal agent of bacterial wilt of many plant species and infects *Capsicum annuum* L., *Solanum tuberosum* L., *Lycopersicon esculentum* Mill., *Solanum melongena* L., *Geranium carolinianum* L., *Zingiber officinale* Roscoe, and a few weed species including *Solanum karsense* Symon, *Celastrus orbiculatus* Thunb., and *Urtica dioica* L. In the presence of a host *R. solanacearum* can be infectious in the soil for many years. Race 3 biovar 2 is easily transmitted by equipment, water, contaminated soil, and insect, or by transplantation of infected seeds or seedlings. Management requires use of resistance cultivars, good cultural practices, clean and certified seed, and some chemicals fumigation, antagonistic microbes as a biological control like transgenic resistant plant, Mycorrhizal fungi, (*Streptomyces* sp. and *Trichoderma* sp.), soil amendments, integrated control, and virulent mutants of *RS* biochemical characterization of *RS* causing bacterial wilt of eggplant in Bangladesh was surveyed by Rahman *et al.* (2010). A survey was conducted on the severity in major eggplant growing areas and basis of bacterial wilt incidence and isolates of *RS* causing bacterial wilt of eggplant. Based on the different location the isolates of this bacterium were arranged in seven groups. Potassium hydroxide solubility test and Gram's staining reported that all groups of this bacterium isolates are gram negative. Four basic sugars (Dextrose, manitol, sucrose, and lactose) were fermented by this bacterium. These results of all biochemical tests with the pathogenicity test confirmed the isolates were *RS* causing bacterial wilt of eggplant. After an incubation period of 24 hours on TZC medium, it was discovered that all groups of *RS* isolates were virulent, creating a light red colour or red core as well as pink and whitish in colour production. On the biovar test clearly reported that all groups of *RS* isolates oxidized four basic sugar like disaccharides (Sucrose, maltose, lactose, and dextrose) and sugar alcohols (sorbitol, manitol, and dulcitol) within 3-5 days and confirmed biovar III. Therefore, it may be confirmed that this bacterium with Biovar III and race 1 causing bacterial wilt of eggplant in Bangladesh. Bacterial wilt of Solanaceae caused by *RS* Race 1 Biovar 3 was investigated by Thera *et al.* (2010). In Mali, the disease is commonly found on *Lycopersicon esculentum* var. *esculentum* L., *Solanum tuberosum* L., *Capsicum annuum* L., *Nicotiana tabacum* L., *Solanum melongena* L., and *Arachis hypogaea* L.; Determination of biovar and race is critical for development of potato seed for management of the disease. Collected the above six plants from fields near Baguineda, Sonityeni, Sotuba, Sikasso, and Kolikoro in which isolates of *RS* isolations were made from dilution plating on triphenyl tetrazolium chloride medium. These isolates were examined for acid production using disaccharide and hexose alcohol carbon sources in tobacco (cv. *xanthi*) host range and hypersensitivity testing. These isolates caused wilt 40 days

post inoculation on greenhouse-grown peanut, tobacco, and tomato plants. Plants inoculated with sterile distilled water were symptomless and identified with Immunostrips. All HR tests were negative. From HR tests of peanut, tobacco, and tomato were indicated that no significant variation was noted between isolates and all isolates were Race 1. From this study, it indicated that the race and biovar of this bacterium from Mali has been reported and this pathogen was widely distributed in Malian soils and surface water has been demonstrated. Cellier and Prior (2010) examined phenotypic diversity of this bacterium strains pathogenic to *Solanum tuberosum* L. They extensively studied 129 Mediterranean and European strains to encompass their genetic diversity. It also indicated that tomato, potato, aubergine, and banana pathogenicity was established between 15°C to 24°C and 24°C to 30°C, respectively. Brown rot phylotype strains IIB-1, IIB-2, and IIB-27 established in bananas, IIA-6, IIB-3 in Moko disease, and IIB-4 in potatoes and tomatoes caused wilt diseases in solanaceous species. Most Mediterranean strains had only tolerance on brown rot phylotype IIB-1 of solanaceous species resistance power. These findings clearly showed that genetically identified strains still need to be understood, mainly through a post-genomics comparative analysis, to understand bacterial speciation in the *RS* species complex. Bacterial wilt drastically limits solanaceous vegetable cultivation in India, according to Ramesh *et al.* (2014). This research gathered 232 *RS* isolates (tomato, aubergine, and chilli) from the different parts of India.

Multiplex PCR and various biochemical tests showed that all *RS* isolates were phylotype I and biovar 3. Sequence examination of 95 isolates' *egl*, *pga*, and *hrpB* genes revealed the genetic diversity of 50 isolates. Indian isolates were divided into two subgroups by *egl* and *pga* genes. Sub group 1 is the dominant group and consists of unknown sequevars, and sub group 2 designated with sequevar numbers based on *egl* sequences. These findings showed that *RS* isolates with unknown or new sequevars have phylotype I diversity due to a continuing evolutionary process.

Potato bacterial wilt in India caused by strains of phylotype I, II, IV of *RS* was studied by Sagar *et al.* (2014). *RS* is a causal organism of bacterial wilt or brown rot diseases of potato. On the basis of biochemical properties and six biovars and the different host range this bacterium is classified into five races. Recently using molecular techniques, this bacterium has been classified into phylotypes on the basis of the intergenic transcribed sequence and the endoglucanase gene sequence. In the recent study, 75 bacterial strains isolated from various wilt infected potato growing regions of India. In this study concluded that *RS* of Indian potato strains belong to 3 out of 4 phylotypes namely: the Asian phylotype I, the American phylotype II, and the Indonesian phylotype IV. In this study first showed that diversity of *RS* from potato using sequevar and phylotype scheme. In mid-Meghalaya, India, this bacterium causes phylotype IV sequevar 8 potato bacterial wilt.

According to Achari and Ramesh (2014) was reported that In the Indian state of Goa, aubergine is one of the solanaceous crops that is grown extensively. It is a crop that is both economically and culturally significant. India. In this study, *RS* is a causal organism of bacterial wilt disease of eggplant which colonizes the xylem tissue. By vacuum infiltration, 167 bacteria were isolated from chili, eggplant, and turkey berry. It also reported that 28 strains prevent the



growth of *RS* and produced volatile antagonistic compounds i.e., XB169, XB86, XB177, and XB200 and plant growth promoting substances. These strains increase in shoot length in eggplant. Identification using 16S rRNA uncovered the existence of 23 distinct bacterial taxa. *Bacillus* sp., *Staphylococcus* sp., *Enterobacter* sp., *Streptomyces* sp., and *Agrobacterium* sp. strains that exhibited high levels of biocontrol with XRB and plant growth promoting activities were identified. In this study, firstly reported that from the xylem of solanaceous crops, identified the bacteria that having traits useful in cultivation of eggplant.

Current Trends in Bacterial Wilt Disease Control Techniques Caused by *RS* surveyed by Nion and Toyota (2015). The current developments in control methods, including biological, physical, chemical, cultural, and integrated ones, as well as the effectiveness and suppression mechanisms of biocontrol, were the main topics of this review. Bacteria (90%) and fungus (10%) have historically dominated BCAs. Well-known BCAs include avirulent strains of *RS*, *Pseudomonas* spp., *Bacillus* spp., and *Streptomyces* spp. The discovery of brand-new or unusual BCAs such *Acinetobacter* sp., *Burkholderia* sp., and *Paenibacillus* sp. Biocontrol effectiveness is impacted by inoculation techniques for BCAs, such as pouring or saturating soil, dipping roots, and seed coatings. It has frequently been observed that the amendment of various organic matters, such as plant residue, animal waste, and simple organic compounds, might decrease bacterial wilt illnesses. The tomato bacterial wilt was shown to be more successfully suppressed when BCAs and their substrates were applied together. The antibacterial metabolites made by BCAs or those found in natural products are often blamed for suppression mechanisms; however, an increasing number of research are focusing on host resistance to the pathogen. Additionally, improved or changed soil microbial populations have a supporting role in the prevention of disease. Utilizing volatile compound-releasing substrates for biological soil disinfection is one of the more innovative and promising forms of control strategies. The pathogenicity of *RS* in tomato seedlings infected with leaf clippings was reported by Kumar *et al.* (2016). A deadly wilt disease is caused by this phytopathogenic bacterium, which colonises the xylem vessels of host plants. Even though its pathogenicity has been the subject of several studies on adult host plants, research on this pathogen's infections of hosts during the seedling stage is less prevalent. In a preliminary observation, *RSF1C1* was inoculated on six to seven days old tomato seedlings using a straightforward leaf-clip technique, which caused a lethal pathogenic condition in the seedlings that ultimately killed them within a week of the inoculation. This prompted study of this inoculation technique's impact on seedlings from various tomato varieties, and similar outcomes were achieved. Using *RSF1C1* that has been GUS-tagged, the colonisation and dissemination of the bacteria throughout the infected seedlings was shown. *RSGMI1000* and separate mutants of *RS* *GMI1000* lacking the virulence genes *hrpB*, *hrpG*, *phcA*, and *gspD* were inoculated into tomato seedlings using the same procedure. On tomato seedlings, the wildtype *RS* *GMI1000* was discovered to be virulent, while the mutants were discovered to be non-virulent. This leaf-clip method for inoculating tomato seedlings has the potential to be an effective strategy, reducing the need for time, space, labour, and money.

According to Kumar *et al.* (2017), Bacterial wilt caused by this bacterium is the most destructive disease of crop plants. In this study, total six isolates wilt disease caused by this bacterium in eggplant and tomato were collected from Karnataka, India. These all the six strains were isolates by simple staining, colonies phenotype, and PCR. It also reported that six isolates were classified into race on the basis of their ability of different host. The isolates 1, 2, 4 and 5 were conducted as race 3 and isolates 3 and 6 were conducted as race 1. Disaccharides (Sucrose, maltose, and lactose) and sugar alcohols (mannitol, sorbitol) can be used in biovar characterization. The ITS sequences of six different strains were determined using sequence analysis and molecular analysis. The results reported that all six isolates are belonged to phylotype I. In conclusion, it was found that this particular bacterium is a causative agent of bacterial wilt, which affects tomato and eggplant plants in Karnataka that belong to Biovar 2, 3, Race 1, 3, and phylotype.

Sharma (2018) examined *RS* morphology and biochemistry in eggplant in Rajasthan. A survey was reported that this bacterium is a causal organism of bacterial diseases of eggplant. By the various test 97 seed samples of eggplant were selected from Rajasthan and these seed samples were grouped as bold discoloured, asymptomatic, and shrivelled discoloured seeds. In this study, the discoloured seeds such symptoms like brown black or water soaked on their surface and using some morphological, molecular characterization and biochemical test identified the bacterium. The seedling shows failure or delayed seeds germination and collapse of hypocotyls and cotyledonary leaves seedling mortality. On the pathogenicity test, the host plant staple seedling roots, tender leaves and roots confirmed *RS* and on HR test in tobacco, the pathogen isolated. Biochemical tests were also used to identify the causative bacterium, and the results showed that *RS* was the cause behind the bacterial wilt of eggplant.

*RS* virulence in eggplant seedlings by the leaf-clip inoculation was evaluated by Phukan *et al.* (2019). This study reported that *RS* is a causal organism of bacterial wilt disease in many important vegetable crops such as tomato and eggplant. The difficulties of this study are that virulence of this bacterium in various host plants is the development of stable pathogenicity assay. Recently described through leaf-clip inoculation method to study it was pathogenicity of tomato seedlings (cotyledon stage) and equally efficient for studying *RS* pathogenicity of eggplant. This study reported that eggplant is highly susceptible to *RS* as compared to tomato seedlings. It also reported or tested the virulence of several regulator mutants of *RS* including *hrpB*, and *phcA* in eggplant seedlings. Although the *phcA* mutant showed a considerable reduction in virulence in tomato, it was only shown to be poor in virulence when tested on aubergine seedlings.

Biology of *RS* and its management in solanaceous vegetable crops was evaluated by Balamurugan *et al.* (2020). In this study, in subtropical, tropical, and some warmer temperate regions, this bacterium is a soil-borne bacterium causing bacterial wilt disease on wider host plants. This bacterium is a causal agent of bacterial wilt disease on solanaceous crops is a serious problem in vegetable cultivation all over the world and it directly affects on host plants with severe yield losses. Many research attempts to control this disease in the field, but all have no success,

because of complex nature of pathogen. Hence, carefully understanding of pathogen biology and its complexity is important before devising disease management strategies. This study is focused upon symptomatology, taxonomy, host range, diversity, pathogen biology, economic impact, pathogenicity determinants, disease cycle, and detection techniques for successful control of bacterial wilt disease, especially in solanaceous vegetables.

A Rapid Pathogenicity Assay of this bacterium in eggplant seedlings by root inoculation approach was surveyed by Singh (2020). In this study, pathogenicity assay of *RS* in eggplant seedlings by root inoculation approach. In case of eggplant, seed germinating period, seedlings age, symptom of the disease is different. *RS* F1C1 inoculation was performed in to 09-11 days old eggplant seedlings result in lethal infection and infected seedlings got wilted within 11 days of post-inoculation. In addition, it also reported that wrapping of the seedlings root by a thin layer of cotton soon after the pathogen inoculation, enhanced the disease progression and wilting of the seedlings stage of eggplant. The standardized root inoculation protocol was found that to be efficient to distinguish mutant strains of different virulence genes such as *phcA*, *hrpB*, and *pilT* from *RS*. Its reproducibility and consistency in different eggplant cultivars, the standardized protocol described the rapid approach to investigate *RS* pathogenicity and disease progressed at the seedling stage of eggplant.

According to Li *et al.* (2021), Tobacco bacterial wilt caused by *RS* is the most serious soil-borne disease of tobacco. In this study, the expressions of susceptible cultivar (Yunyan 87) and resistant cultivar (Fandi 3) at various stages after *RS* infection were compared to molecular mechanisms of tobacco resistance against this bacterium. From results they were understand that the number of upregulated expressed genes (DEGs) at 3- and 7-days post-inoculation increased in the resistant cultivar. The WRKY6 and WRKY11 family genes in WRKY transcription factors, the ERF5 and ERF15 family genes in ERF transcription factors and the PR5 genes were all upregulated in response to infection in the resistant cultivar. In the resistant cultivar, DEGs encoding CYP450, TCM, CCoAOMT, CCR, CSE, and CADH, involved in synthesis of plant antitoxins such as flavonoids, lignin's and stilbenoids, enriched in the upregulated at 3 and 7 dpi. This study has strongly understood of molecular interactions between tobacco plants and this bacterium. Analyzing the bacterial wilt biocontrol methods used in tobacco and other Solanaceae to combat the deadly pathogen *RS* was surveyed by Ahmed *et al.* (2022). The global production of Solanaceae and flue-cured tobacco crops is seriously threatened by the bacterial wilt disease produced by the *RS* species complex. *RS* colonises the vascular system, invades plants through the roots, and inhibits xylem tissues. Parts of above-ground plants exhibit typical unilateral withering signs, which cause plant loss. In order to reduce the incidence of bacterial wilt disease, integrated disease management measures have been used for many years. These strategies include cultural control, chemical control, and genetic resistance. Due to the disease's high genetic diversity, wide host range, and long-term survival of the pathogen in soil and on plant parts, none of these treatments have entirely eradicated the disease. The ideal method for protecting human health and the environment is biological control, which is made possible

through co-management solutions. Endophytes and rhizobacteria, which are present in all plant parts (leaves, stems, roots, and rhizosphere), play a vital part in the treatment of diseases and the promotion of the growth of plants. The diverse interactions between the host, pathogen, and antagonists that may be involved in potential biocontrol strategies include niche exclusion, nutrition acquisition, direct antagonism, induction of resistance, and synthesis of antimicrobial chemicals. In greenhouse experiments, studies have demonstrated that biocontrol agents effectively lower the incidence of the bacterial wilt disease, but outside trials have not yielded positive results. We tried to condense the information on microbe-assisted biocontrol of plant pathogens in this review with a particular emphasis on the bacterial wilt disease of flue-cured tobacco and solanaceous crops.

### Future perspectives and emerging challenges

Fields must be kept free of soil pathogens through preventative measures. As *RS* may survive for a long time in soil, water, and plant matter, it is essential to disinfect seeds, soil, and water in order to increase agricultural output by preventing this disease. It is also necessary to investigate the dynamics of the pathogen as well as its genetic diversity for better understanding of the effects of the factors related to the geography and the environment on the composition of the *Ralstonia* spp. population. However, it is very crucial to detect *RS* in soil and water as early as possible in order to prevent the pathogen from spreading to new areas. Recent progress in research has resulted in the development of a sensitive quantitative method for detecting *RS* in the soil. This particular method is mainly based on the most probable number analysis of the PCR data. Using this innovative method, infections can be identified even when they are present in extremely trace amounts.

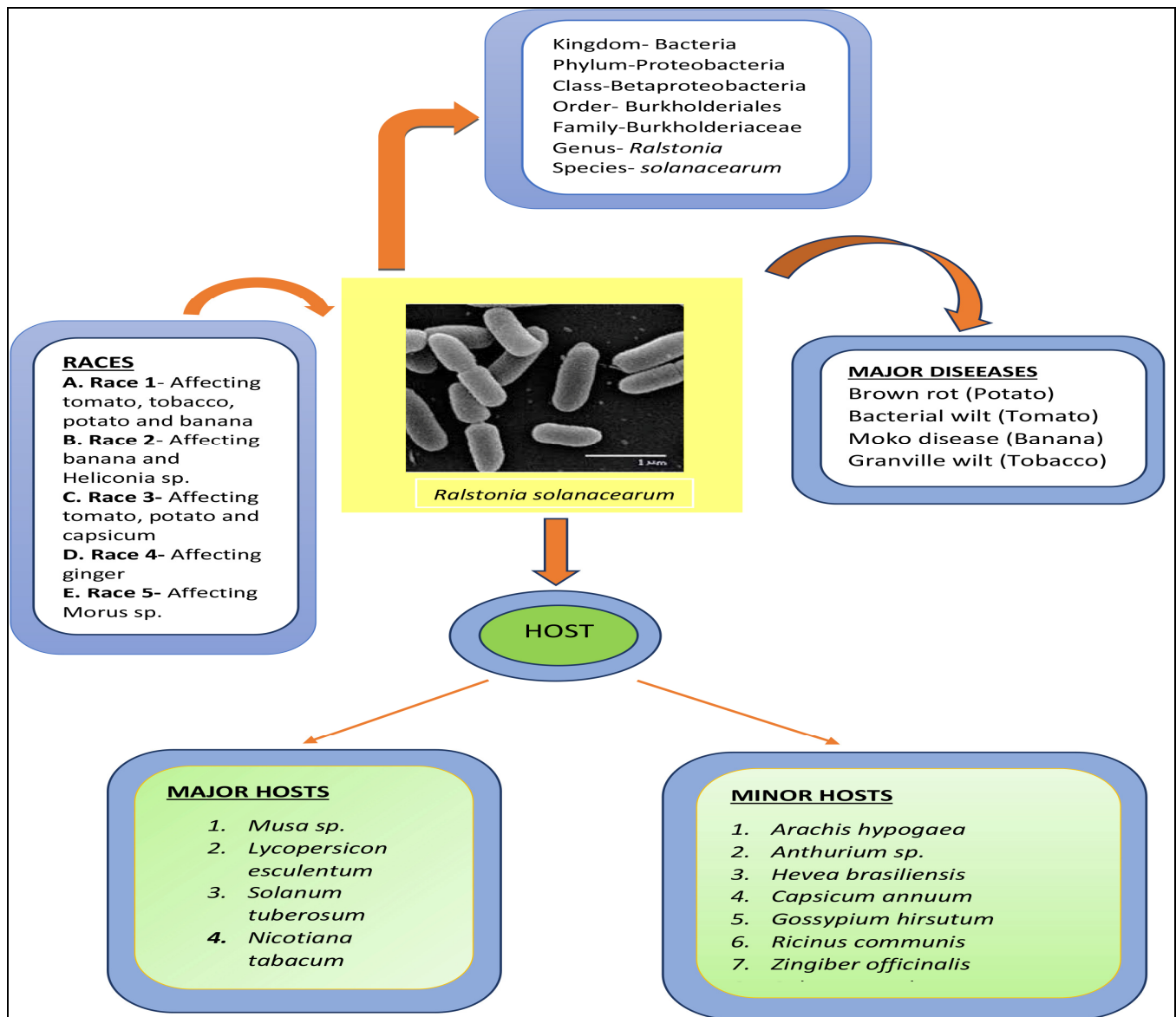
On the other hand, currently, various nano-technological approaches are being conducted as these approaches offer a workable alternative for the efficient control of *RS* induced plant diseases (Khan *et al.*, 2021; Guo *et al.*, 2022). It has been also shown that nanoparticles have the potential to operate as both a biosensor and an antibacterial agent in order to detect plant diseases, particularly those caused by soil-borne pathogens (Khairy *et al.*, 2022). Different metallic oxide nanoparticles are being utilized to check whether or not they have the ability to act as protective agents against *R. solanacearum*. Recent research works have focused on the effectiveness of nanoparticles (NPs) containing ZnO, FeO, and CuO in combating the bacterial wilt pathogen *RS*. According to the data, NPs, and specifically CuONPs, significantly reduced the frequency with which tomato was affected by illness. Following foliar application of chitosan NPs to pathogen-infected plants, in vivo tests showed a decrease in the severity of the disease. The Chitosan NPs were found to directly interact with the bacterial cell wall, resulting in shape alterations, flagella loss, and lysis. Chitosan NPs loaded with silver nanoparticles showed antibacterial activity against this bacterium (Santiago *et al.*, 2019). *RS* is physically and chemically constrained vertically and horizontally by plant resistance (Planas-Marquès *et al.*, 2019). Plants that are resistant to this bacterium trap the pests instead of killing them. The robust framework of the plant serves as the basis for this strategy for preventing vascular diseases. This bacterium and plants compete and change over time, employing various strategies

to deceive one another. For the upcoming breeding stage, it is essential to figure out the efficient mechanisms of resistance against this bacterium in resistant plants.

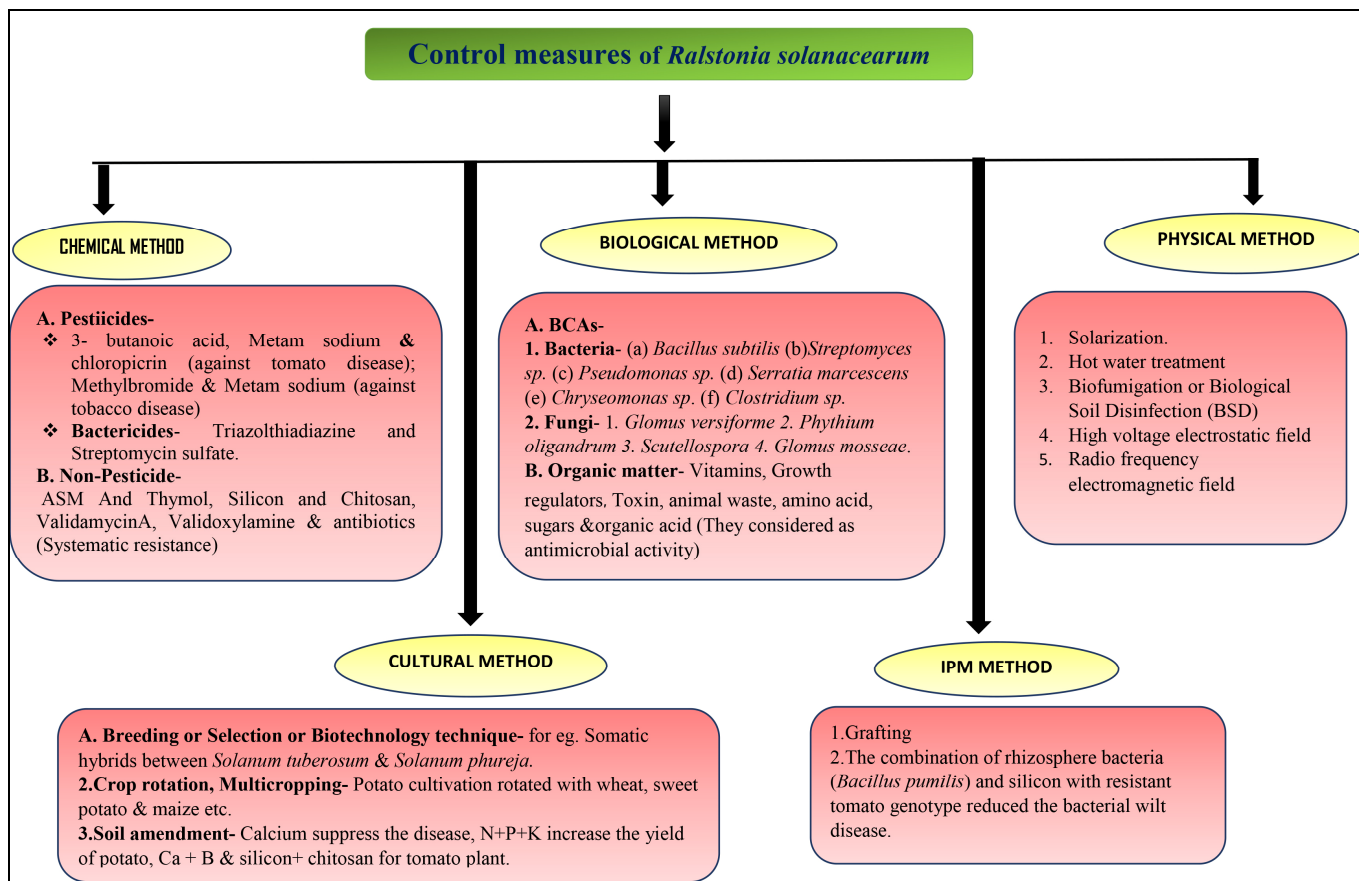
### Conclusion

Thus, the hazardous soil-borne pathogen RS, which causes fatal bacterial wilt diseases in solanaceous crops like potato, tomato, eggplant, banana, and tobacco, was originally detected as a Gram-positive rod 126 years ago. Much has been learned about it since then. Many names have changed as phenotypic, biochemical, and molecular research grows into genomes and functional genomics. After genomic analyses of strain phylogenetic linkages indicated their relationships, RS was placed in a "species complex". Given that RS is unique, has numerous hosts, and is widespread. Researchers are now able to go beyond studies that are based on MLST in order to explain strain variety and evolutionary linkages because the cost of genome sequencing has decreased. In 2015, just 10 genomes were fully analyzed. In 2020, 18 years after the first genome sequence for RS was released, NCBI GenBank included 217 full genome sequences for all three RSSC species, *R. solanacearum*, *R. pseudosolanacearum*, and *R. syzygii*. Genomic materials for

phylotypes I and IIB are abundant, whereas IIA, III, and IV are scarce. Wicker *et al.* (2012) observed that phylotype III and IV strains have the highest variation and phylotype I strain has the least. RS on solanaceous crops is a global concern that causes considerable yield losses. Bacterial wilt is difficult to control due to its diversity, ability to survive in varied environments, latent infection in plants, and lengthy life on soil. Chemical insecticides suppress bacterial infections. Pesticides lose efficacy with time; most are expensive and have environmental and health risks. No management practice, including bio-fumigation, grafting, and breeding resistant crop cultivars, has wholly suppressed the disease. The disease is difficult to control due to pathogen resistance to widely used pesticides and the loss of methyl bromide and other soil fumigants. For effective management of RS-related fatal diseases, new and better approaches, particularly more effective BCAs, are needed. Thus, this review also highlights a few intriguing directions in which future research on this bacterium may go. It's vital to comprehend how complicated this bacterium is and employ the proper techniques to deal with it in order to prevent it from damaging the agricultural sector.



**Fig. 1:** Diagrammatic representation of different races of *R. solanacearum* (Smith) Yabuuchi causing major diseases and associated host plants.



**Fig. 2:** Brief outline of the various control measures of the diseases caused by *R. solanacearum* (Smith) Yabuuchi.

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