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REVIEW ARTICLE

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Do agroecological practices control *Ralstonia solanacearum* wilt on solanaceous crops? A meta-analysis

Moukaïla Bagri Bouraïma[1,2] | Charles L. Bielders[2] | Rachidatou Sikirou[3] | Vincent Awe Ezin[4] | Bonaventure Cohovi Ahohuendo[5] | Enoch G. Achigan-Dako[1]

[1]Genetics, Biotechnology and Seed Sciences Unit (GBioS), Laboratory of Crop Production, Physiology and Plant Breeding, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

[2]Earth and Life Institute - Environmental Sciences, Université Catholique de Louvain, Ottignies-Louvain-la-Neuve, Belgium

[3]Laboratory of Crop Protection, Research Center of Agonkanmey (CRA-Agonkanmey), National Institute of Agricultural Research of Benin (INRAB), Abomey-Calavi, Benin

[4]Laboratory of Crop Production, Physiology and Plant Breeding, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey Calavi, Benin

[5]Faculté Des Sciences Agronomiques, Université d'Abomey-Calavi, Abomey-Calavi, Benin

Correspondence
Moukaïla Bagri Bouraïma, Genetics, Biotechnology and Seed Sciences Unit (GBioS), Laboratory of Crop Production, Physiology and Plant Breeding, Faculty of Agronomic Sciences, University of Abomey-Calavi, Benin.
Email: bagrimoukaila@gmail.com

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Abstract

The effectiveness of agroecological management strategies (AEMS) in controlling bacterial wilt caused by *Ralstonia solanacearum* species complex (RSSC) remains a critical question. A quantitative review was conducted based on publications reporting agroecological bacterial wilt management practices under on-station or on-farm field conditions in electronic libraries, without geographical restrictions, on tomato, pepper, eggplant and potato. After applying inclusion and exclusion criteria, 48 papers were retained, resulting in 644 and 146 observations of bacterial wilt incidence (BWI) and yield, respectively. The effectiveness of AEMS for each crop was evaluated based on BWI and crop yield. The effect size was calculated as the natural logarithm of the response ratio, and confidence intervals were determined by bootstrapping. Varietal control, biological control (used of biological control agents) and combinations of many AEMS were the most reported practices, both under on-station and on-farm conditions. The use of plant extracts (*Thymus* spp., *Crotalaria* spp.), grafting, solarization, soil amendments (manure, compost) and crop rotations (with maize, beans) were also reported. All AEMS significantly reduced bacterial wilt incidence and increased yields compared to the untreated plots. Grafting, combinations of control methods, varietal control and biological control were the most effective agroecological practices in reducing BWI and increasing yield in tomato and eggplant. Varietal control was the most effective compared to biological control on pepper. The effectiveness of AEMS also varied with crop susceptibility and origin, climatic zone and soil acidity. This study highlights the potential of AEMS in reducing BWI and increasing crop yield in infested soils.

KEYWORDS
bacterial wilt management, eggplant, pepper, potato, soilborne disease, tomato

1 | INTRODUCTION

Bacterial wilt was first reported in 1896 on potato in Japan. This disease is caused by the *Ralstonia solanacearum* species complex (Smith, 1896; Yabuuchi et al., 1995). With nearly 7794 strains isolated in 100 different countries across tropical, subtropical and temperate zones (Lowe-Power et al., 2020), managing these bacteria presents a major challenge in various critical cropping systems due to their pathogenicity, diversity and global distribution. In particular, race 3, biovar 2 (R3bv2) of the species complex has been attributed the A2 quarantine international status and is considered as a bioterrorism agent in the United States (Lambert, 2002).

Previously known as *Pseudomonas solanacearum* or *Burkholderia solanacearum*, *R. solanacearum* is a gram-negative, single-celled bacterium ranging in size from 0.5–0.7 μm to 1.5–2.0 μm with one or more flagella (Sneath et al., 1986; Yabuuchi et al., 1995). With the evolution of phenotypic and genomic characterization tools, *R. solanacearum* has undergone several systematic classifications since its discovery, ranging from the one proposed by Buddenhagen (1962) to the more recent ones proposed by Fegan and Prior (2005), Safni et al. (2014) and Prior et al. (2016). The genus was renamed *Ralstonia solanacearum* species complex (RSSC) and reorganized into three different major species, classifying phylotypes I and III as *R. pseudosolanacearum*, phylotype II as *R. solanacearum* and phylotype IV as *R. syzygii* (Prior et al., 2016; Safni et al., 2014). RSSC can adapt to and survive in different types of environments (soil or water; host and non-host plants) under temperatures ranging from 10 to 41°C, which makes them adaptive pathogens (Kelman, 1953; Sikirou et al., 2017).

Due to its genomic plasticity, the RSSC is known to infect many species from many different botanical families (Denny, 2000; Genin & Denny, 2012; Hayward, 1964; Persley & Batugal, 1986). It is ranked as causing the second most important disease in plant production, affecting a broad range of economically important crops such as tomato, eggplant, potato, tobacco, pepper and banana (Bihon et al., 2020; García et al., 2019; Mansfield et al., 2012). Yield losses can vary from 10% to 100% depending on the strain of the pathogen, the host crop, the cultivar, the presence or absence of secondary hosts, climate (especially through temperature and soil moisture content), agricultural practices, as well as physical, chemical and biological soil conditions (Hayward, 1991; Michel & Mew, 1998; van Elsas et al., 2000).

Many management strategies have been developed over time to deal with RSSC under different environmental conditions. Since the 1970s, pesticides such as acibenzolar-*S*-methyl (Pradhanang et al., 2005), metam sodium, 1,3-dichloropropene and chloropicrin (Yuliar et al., 2015) have been tested by scientists for the management of soilborne diseases (Chellemi et al., 1997), including bacterial wilt, because of low application cost and ease of application. However, generally, these chemical pesticides have limited efficacy because of the complexity of the pathogen (Osdaghi, 2020; Wang et al., 2023; Yuliar et al., 2015). Likewise, because of the potential adverse environmental and health effects of these pesticides, crop protection strategies have gradually been evolving from a curative approach based on agrochemicals to a preventive approach based on good agricultural practices in controlling bacterial wilt (Osdaghi, 2020) and a more balanced and sustainable ecological functioning of agroecosystems (Deguine et al., 2017). This approach relies on crop diversification in space and time in view of promoting interactions between agroecosystem components but also on improving soil quality by means of ecological cropping practices. Called agroecological crop protection (ACP), it embodies the application of the three dimensions (environmental, economic and social) of agroecology to crop protection (Deguine et al., 2017; Wezel & Soldat, 2009). This holistic approach prioritizes farmers, considering their socio-economic circumstances, the crops, the field, the farm, the landscape and territory indigenous knowledge and collaborative networks when protecting the environment through sustainable practices (Deguine et al., 2021, 2023; Vega et al., 2023). During recent decades, agroecological and sustainable alternatives have therefore been developed against bacterial wilt, such as crop sanitation, host resistance, biological control, use of botanical extracts (botanical control), crop rotations, crop associations, organic amendments, solarization, grafting and the combination of several such control methods (Adebayo, 2011; Ayana & Kurabachew, 2016; Guo et al., 2004; Huet, 2014; Ramesh & Phadke, 2012; Yadessa et al., 2010). For example, Rivard et al. (2012) evaluated grafting management methods on tomato in three different regions of the United States. Their results show that bacterial wilt incidence (BWI) on grafted plants was 21%, 8.5% and 0% in contrast to the ungrafted plant, where BWI was 82%, 88% and 82%, respectively, for each region. Adhikari and Basnyat (1998) reported a reduction of 20%–26% of BWI on tomato partially resistant lines after maize and cowpea while Ayana and Fininsa (2017) reported an average incidence reduction of 6% and 16% on tomato cultivated after maize and common beans. On the other hand, this reduction was 94% on potato cultivated after maize, sorghum or millet. Likewise, tomato grown in rotation with *Crotalaria juncea* reduced BWI by 86% (Deberdt et al., 2015). Using resistant varieties has been shown to reduce BWI by 78% by Lin et al. (2004) and by 90%–100% by Fock et al. (2000). Incorporating 20%–30% (vol/vol) of the aerial parts of *Crotalaria* species as organic matter completely eliminated tomato bacterial wilt according to Cardoso et al. (2006). In contrast, Fontem and N'tchorere (2009) reported a 60% reduction in bacterial wilt in potatoes when 11% (vol/vol) of *Crotalaria* leaves were incorporated into infested soil. The efficacy of many other plants such as *Brassicaceae* species and *Thymus* species have been reported. Biological control agents (BCAs) have also been successfully used to control RSSC. Whereas Yuan et al. (2014) reported a reduction of BWI of 18%–60% on tobacco after pouring a suspension containing *Bacillus amyloliquefaciens* onto the plants, Hu et al. (2010) observed reductions of BWI from 60% to 87% on pepper. Many other BCAs such as *Bacillus subtilis*, *Pseudomonas fluorescens*, *P. aureofaciens*, *P. syringae*, *P. chlororaphis* and *Streptomyces* have been reported, with variable performance (Dey et al., 2014; Figueiredo, et al, 2010). That is why Chandrasekaran et al. (2016) conducted a meta-analysis to identify the most effective BCAs among the various options for biological control of RSSC. It therefore appears that these different agroecological approaches can, under some circumstances, be effective at reducing the incidence of bacterial wilt, albeit to varying degrees depending on the practice and the crop species. Also, the effectiveness of these techniques may depend on environmental or management-related factors, but this has not been reviewed systematically.

Thus, in order to achieve a better understanding of the effectiveness of various control methods, we performed a meta-analysis to measure the effect of agroecological bacterial wilt management methods (use of resistant or tolerant varieties, grafting practices, use of botanical extracts, use of biological control agents, crop rotation, crop association and their combinations) in reducing the incidence of bacterial wilt caused by RSSC and in increasing the yields of tomato, pepper, eggplant, African eggplant and potato compared to an untreated control. Additionally, we aimed to determine which environmental and management factors influence this effect.

2 | METHODOLOGY

2.1 | Literature research

The study focused on tomato (*Solanum lycopersicum*), potato (*Solanum tuberosum*), pepper (*Capsicum* spp.), eggplant (*Solanum melongena*) and African eggplant (*Solanum macrocarpon*). Potato, tomato, eggplant and pepper are the four main cultivated edible solanaceous crops in the world (Morris & Taylor, 2017). In the same way, African eggplant is one of the most cultivated leaf solanaceous crops in West Africa. The Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Moher et al., 2009) article selection process was used (Figure 1). The database was constructed through an advanced search of the Scopus, Web of Knowledge and Google Scholar electronic databases using the search equation ('bacterial wilt' OR '*R. solanacearum*' OR '*Pseudomonas solanacearum*' OR '*Bacillus solanacearum*') AND ('control*' OR 'management' OR 'suppress*') AND ('tomato' OR '*Lycopersicum esculentum*' OR 'pepper' OR '*Capsicum*' OR 'African eggplant' OR '*Solanum macrocarpon*' OR 'potato' OR '*Solanum tuberosum*' OR 'eggplant' OR '*Solanum melongena*'). The search was limited to published primary articles in English and French until October 2021 without geographical restriction.

Screening by title, abstract and content was performed to clean the database. Only articles dealing with the management of bacterial wilt on tomato/pepper/potato/eggplant/African eggplant were retained. Abstract screening consisted of selecting articles that tested at least one agroecological bacterial wilt management strategy (preventive methods, use of resistant or tolerant varieties, grafting, use of botanical extract, use of biological control agents, crop rotation, crop association and their combinations) and measured disease intensity (BWI and/or bacterial wilt severity and/or area under disease progress curve [AUDPC] and/or disease index [DI]) for at least one of the five crops of interest. During data collection, only papers reporting on-station or on-farm field trials were included in the database. Articles that did not report results from an infested soil without management practice as a control were also excluded. From the database, each documented agroecological bacterial wilt management practice considered in our study was extracted and used as an observation. Chemical observations were also excluded from our study.

After application of the inclusion and exclusion criteria, 644 bacterial wilt incidence observations were extracted from 48 original papers. However, only 18 papers out of 48 reported crop yields, resulting in 146 observations.

2.2 | Data acquisition

The explanatory variables used to measure the effectiveness of the various management methods for RSSC were the BWI and crop yield. Indeed, too few studies reported bacterial wilt severity, AUDPC or DI. Hence these variables were discarded. The average of BWI for each observation, the number of replicates (*n*), standard error of the means (*SE*) or standard deviation (*SD*) of the variables were extracted when available. Equation 1 was used to convert *SE* into *SD*. In case where coefficient of variation (CV) and treatment mean

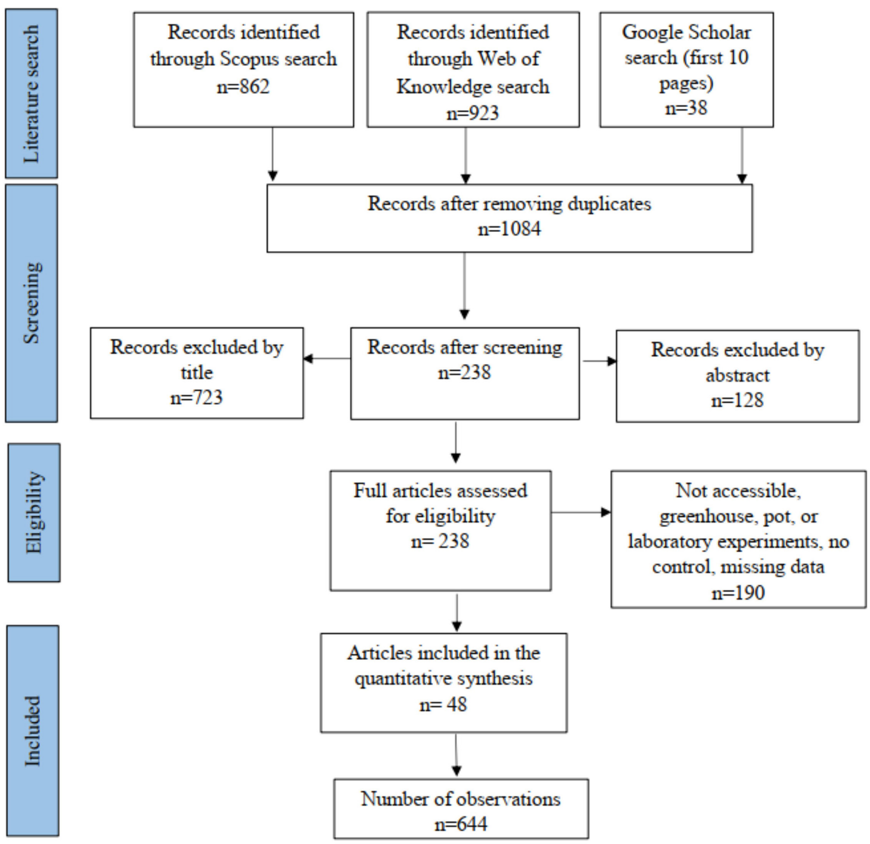


FIGURE 1 PRISMA flow diagram detailing the screening process of articles included in the analysis (Moher et al., 2009).

($\bar{Y}$) were reported, these were used to calculate the standard deviation (Equation 2). When averages were provided in graphical form, WebPlotDigitizer (Rohatgi, 2015) was used to extract these values.

$$SD = SE \times \sqrt{n} \tag{1}$$

$$SD = CV \times \overline{Y} \tag{2}$$

2.3 | Moderator variables

The race of RSSC (1, 2, 3 or 4), the phylotype (1, 2, 3 and 4) and the type of infection (natural or artificial) were extracted from each study when available. The control strategy, crop, treatment support (seed, plant, soil, plant & soil, seed & soil, seed & plant & soil) and the environmental conditions (temperature, precipitation), type of climate, type of experiment (on-station trial or on-farm trial), crop variety (local or improved), variety susceptibility (bacterial wilt resistant or susceptible) and bacteria inoculation support (plant, soil, seed or plant & soil) were recorded as moderator variables that may influence the effectiveness of the agroecological management strategies (AEMS).

When site coordinates were not mentioned, we used Google Earth to collect them online by means of the experimental site name. Climatic data were collected using Cropwat and Climwat databases developed by FAO based on the geographical coordinates of experimental areas. Study areas were classified into humid, dry-subhumid, semi-arid, arid and hyper-arid zones using the bioclimatic index developed by UNEP (1997). Soil pH was derived from the soil grid database available online (https://www.isric.org/explore/soilgrids) based on the geographical coordinates of experimental sites. Soils were classified into extremely acidic (3.5–4.4), very strongly acidic (VSA: 4.5–5.0), strongly acidic (SA: 5.1–5.5) and moderately acidic (MA: 5.6–6.0) using the United States Department of Agriculture Natural Resources Conservation Service classification (https://www.nal.usda.gov/natural-resources-conservation-environment/soil).

2.4 | Response ratio calculation

The response ratio as described by Gurevitch and Hedges (1999) was calculated as the natural logarithm of the ratio between management practice mean and control mean. In contrast to the standardized difference of means previously proposed by Hedges and Olkin (1985), the response ratio linearizes the metric (Gurevitch & Hedges, 1999) and thus reduces the risk of non-normally distributed data (Johnson & Curtis, 2001; Tonitto & Ricker-Gilbert, 2016).

2.5 | Data quality assessment and statistical analysis

The calculated response ratio can be subject to bias resulting from research publication bias or missing data. To evaluate this, publication bias and sensitivity analysis were performed using a fail-safe number (Rosenberg, 2005). In fact, publication bias can be ignored when the number of observations needed to nullify the response ratio is over $5n+10$, where n is the number of observations included in the analysis. Also, a funnel plot was plotted to check for publication bias. This is a scatter plot of the response ratio estimated from individual studies against some measure of each study's size or precision (Sterne et al., 2011). In the absence of publication bias, 95% of studies should be inside the triangle and symmetrically distributed (Begg & Berlin, 1988; Sterne et al., 2011). The Egger et al. (1997) regression test was also combined with this test to assess asymmetry in the distribution of studies. Trim-and-fill tests were also used to make sure that complementary data were not required before performing subgroup analysis (Duval & Tweedie, 2000). The method uses a measure of asymmetry in funnel plots to first detect the extent of publication bias and then corrects it by trimming data points that increase asymmetry and filling in data points to counterbalance until symmetry is reached (Sterne et al., 2011). The effectiveness of each control method is measured marginally by calculating the subgroup response ratio using the restricted maximum-likelihood approach (Hedges et al., 1999). In fact, if studies with "poor" results are less likely to be published, this approach simultaneously estimates the proportion of studies censored, the threshold past which censorship is avoided and the probability of censorship if a potential observation is under the censorship threshold (Rust et al., 1990). Each response ratio was pooled using the nonparametric weighting formula described by Hedges and Olkin (1985) (Equation 3). The confidence interval was then determined by using the resampling method called bootstrapping described by Adams et al. (1997) and Lajeunesse (2015). Given that the efficacy of the pathogen management method can be subject to various environmental parameters, the random-effect model was used to compare the different practices evaluated against each other (Borenstein et al., 2010; DerSimonian & Kacker, 2007). The response ratio of each group was considered significantly different from the control when the confidence interval did not contain zero. In addition, management methods were considered significantly different from each other when their confidence intervals did not overlap (Chivenge et al., 2011; Tonitto & Ricker-Gilbert, 2016). These statistical analyses were carried out with OpenMee software (Wallace et al., 2016) and the metaphor package using the R v. 4.1.3 software (http://www.R-project.org).

$$\mathrm{Wi} = \frac{nXE \times nXC}{nXE + nXC} \tag{3}$$

where Wi = study weight, XE = treatment mean, XC = control mean and n = number of observations (Hedges & Olkin, 1985).

3 | RESULTS

3.1 | Geographical distribution of the studies included in the meta-analysis

Several management practices of bacterial wilt have been tested on-station or on-farm across almost all continents where the bacterium has been reported at least once according to the GBIF database (GBIF, 2018; https://www.gbif.org/fr/) and European and Mediterranean Plant Protection Organization database (EPPO, 2014). Humid zones were most represented. The greatest number of observations was from the Asian continent (Figure 2). The results of the descriptive analysis applied to the absolute value of BWI (%) and crop yields (t/ha) recorded on untreated and treated plots are summarized in Table 1. Generally, BWI was higher and crop yields were lower on untreated plots compared to those that received AEMS.

3.2 | Data quality

Funnel plots showed that more than 95% of the studies are found within the funnel for both BWI and yield response ratios (data not shown). These results were confirmed by the trim-and-fill test, which revealed that no complementary data was required for BWI response ratio (Figure 3a) and yield (Figure 3b) to ensure a symmetrical distribution of points in the funnel. In the same way, Egger's regression test indicated no significant publication bias ($t=-0.1218$, $df=642$, $p=0.8975$ for BWI response ratio; $t=0.2616$, $df=144$, $p=0.79$ for yield response ratio). Finally, the fail-safe number analysis also showed that more than $5n+10$ studies were necessary to modify the general effect size calculated.

3.3 | Effect of management and moderator variables on BWI and crop yield response ratios

Published data pertained to eight main AEMS for bacterial wilt that were tested in on-station or on-farm trials for tomato, potato, eggplant and pepper. No data was found for African eggplant. The reported AEMS are biological control, botanical control (Ngegba et al., 2022), varietal control (use of resistant or tolerant varieties), solarization (heat treatment of the soil), grafting (grafting a scion susceptible to RSSC onto a rootstock that is resistant or tolerant), crop rotation (succession of susceptible crops with sanitation crops or no-host plants), organic amendments, and a combination of such management methods (named “Combination”).

The overall means for each crop and performance of AEMS on BWI and yield response ratios for on-station and on-farm trials is summarized in Figure 4. AEMS significantly reduced the incidence of the disease in tomato, eggplant, potato and pepper (Figure 4a). They also significantly increased yield compared to the untreated control.

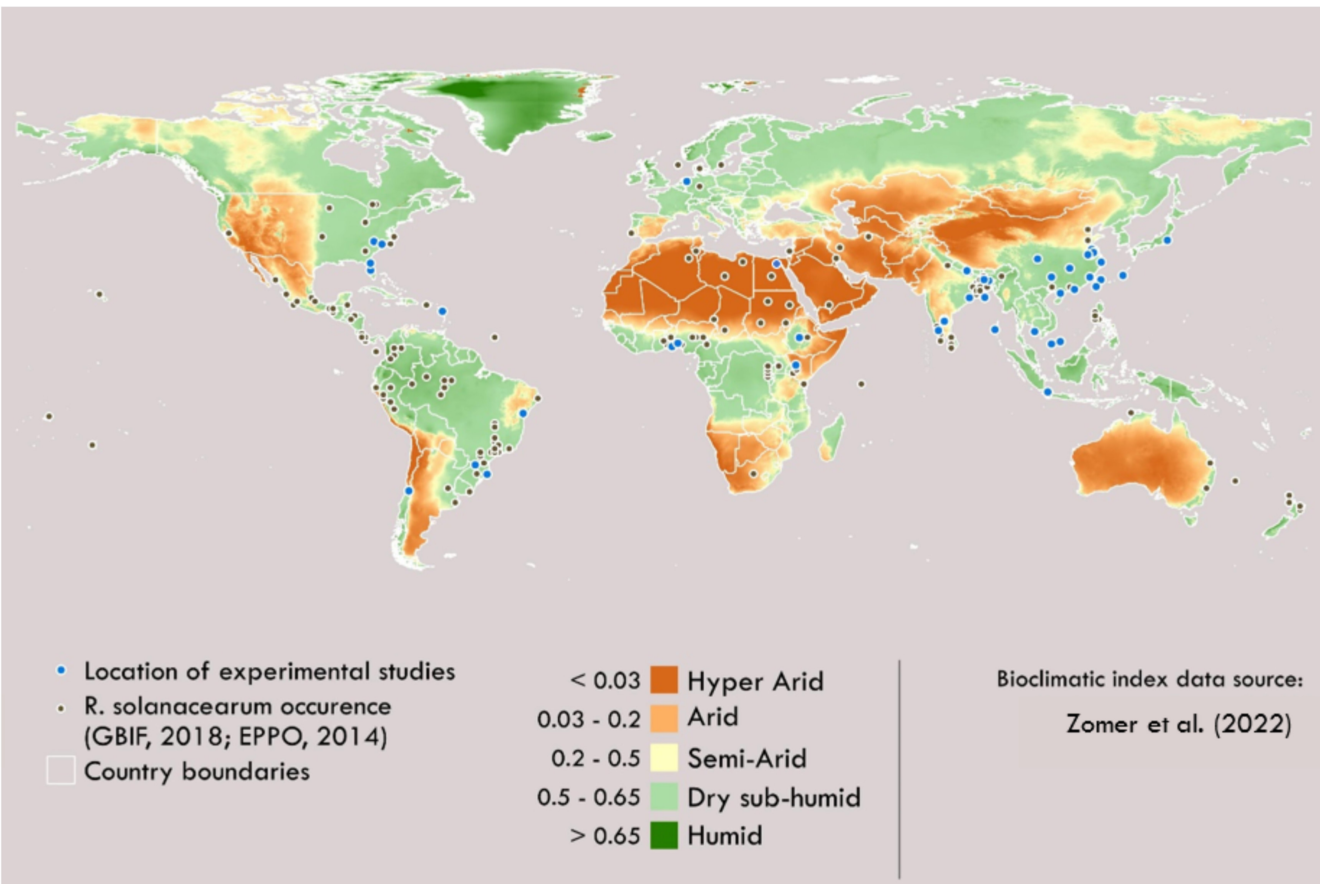


FIGURE 2 Location of experimental studies used in the present meta-analysis and distribution of *Ralstonia solanacearum* species complex occurrences according to the GBIF (2018) and EPPO (2014) databases. Locations are projected on the bioclimatic index map of Zomer et al. (2022).

However, on average, the AEMS appeared to be more effective for eggplant, tomato and pepper than for potato. Consistent with this, yield increases were lower for tomato and potato than for eggplant (no data for pepper yield).

Irrespective of the crop, all AEMS applied on-station or on-farm significantly reduced the BWI response ratio compared to the untreated control. No significant difference was observed in the effectiveness of AEMS between on-station and on-farm trials in terms of BWI response ratio (Figure 4a). AEMS also significantly increased the yield of tomato, potato and eggplant compared to the untreated control. For the yield response ratio, the difference between on-station and on-farm conditions was significant for tomato (Figure 4b). The yield response ratio was 0.797 (n=39; CI_95%: 0.974–1.168) for on-station and 0.503 (n=43; CI_95%: 0.506–0.637) for on-farm trials (Figure 4b). No significant difference was found for eggplant.

When assessing the efficacy of various AEMS, all methods demonstrated a significant reduction in the BWI response ratio compared to the untreated control (Figure 5a). Grafting exhibited the most substantial reduction, significantly outperforming all other management methods for tomato and eggplant. It was followed by varietal control and combinations of management methods for these crops. Regarding pepper, varietal control was more effective than biological control (Figure 5a). However, for potato, no significant difference was found in the reduction of the BWI response ratio among all reported AEMS.

Consistent with the BWI results, all AEMS significantly increased crop yields for tomato, eggplant and potato (Figure 5b) compared to the untreated control. No data was obtained for pepper yield. Biological control exhibited the highest response ratio for tomatoes, although it was not significantly different for combinations of management methods and grafting. For eggplant, varietal control and combination led to significantly higher yields compared to botanical control and soil amendment. For potato, data were reported only for soil amendment yield.

Due to insufficient data, highly susceptible, moderately susceptible and susceptible varieties were combined into a single 'susceptible varieties' category, while highly resistant and tolerant varieties were grouped into a 'tolerant varieties' category. BWI response ratio values were significantly lower in tolerant varieties than in susceptible varieties, indicating that AEMS were more effective with tolerant varieties than with susceptible varieties across all agroecological control methods for tomato and eggplant (Figure 6a). For potatoes, the BWI response ratio was equal between susceptible and tolerant varieties. The yield response ratio followed the same trend as the BWI response ratio for tomato and eggplant (Figure 6b). No data was found for pepper and potato yield.

BWI response ratio AEMS was not significantly affected by the bacteria inoculation support used in order to induce the disease (plant or soil; Figure 7a). In contrast to BWI, crop yield response ratio varied significantly with the inoculation support for tomato (Figure 7b). AEMS were less effective when RSSC were inoculated in soil than directly on plant tissue in order to induce the disease.

TABLE 1 Descriptive statistics of bacterial wilt incidence (%) and yield (t/ha) recorded in papers included in this review.

Crop	Incidence (%) Untreated plots	Incidence (%) AEMS plots	Yield (t/ha) Untreated plots	Yield (t/ha) AEMS plots
Tomato	65.5±23.6 (n=282)	27.4%±26.2 (n=282)	23.6±15.8 (n=98)	51.2±38.8 (n=98)
Pepper	90.8±25 (n=72)	40.3±35.5 (n=72)	–	–
Potato	60±23.95 (n=198)	38.2±23 (n=198)	22.9±3.6 (n=4)	32.4±3.7 (n=4)
Eggplant	91±15.25 (n=92)	20±13.88 (n=92)	5.8±17 (n=44)	21±18.7 (n=44)

Abbreviation: AEMS, agroecological management strategy.

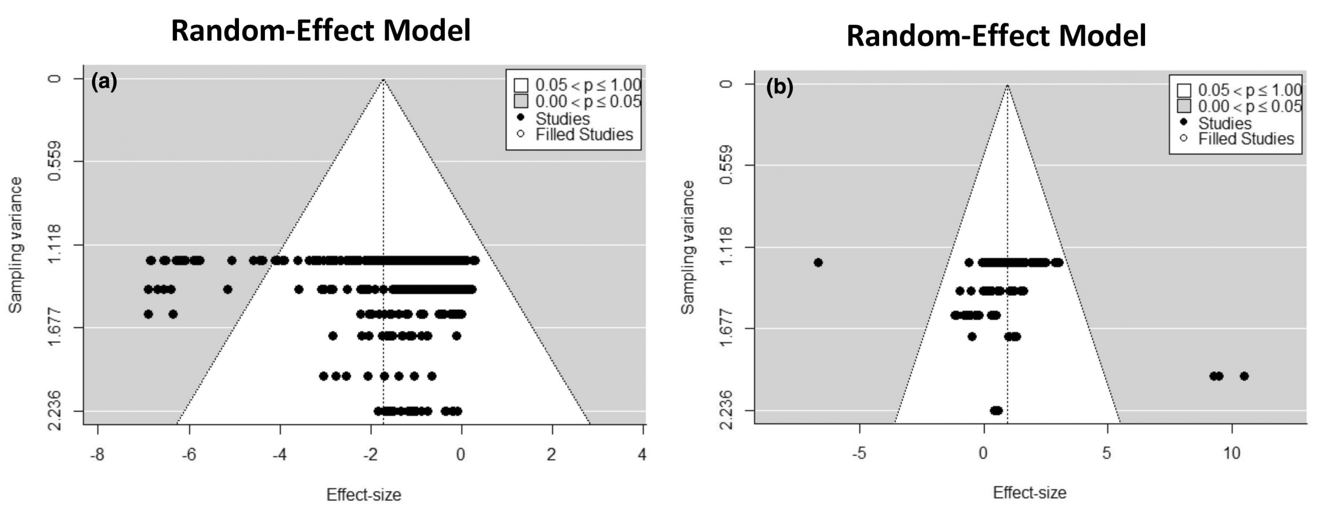


FIGURE 3 Trim-and-fill test applied to bacterial wilt incidence (a) and yield (b) response ratios.

FIGURE 4 Bacterial wilt incidence (BWI) (a) and yield (b) response ratios (RR) as affected by the type of experimental site. Because of insufficient data, the yield response ratios for pepper could not be analysed.

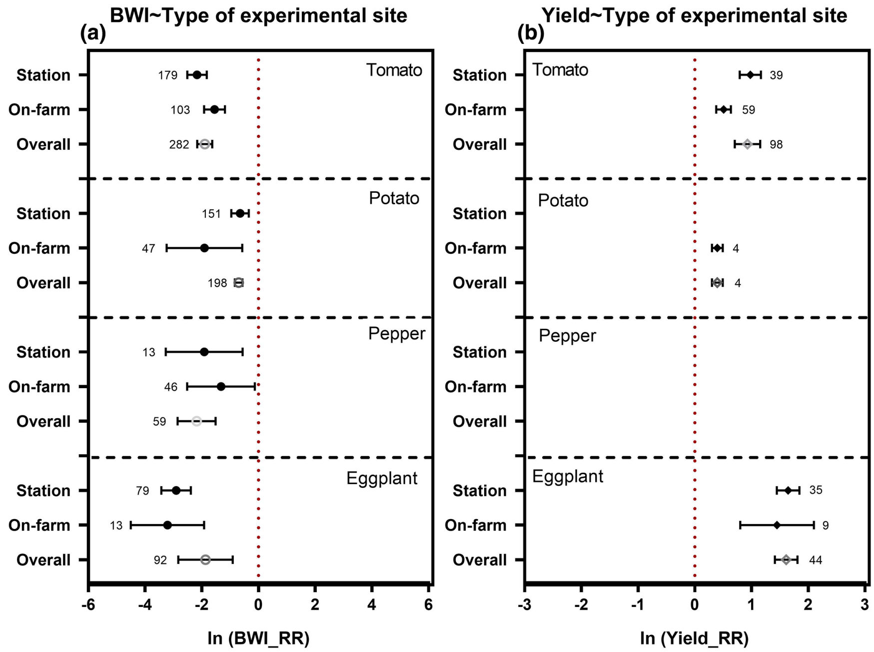
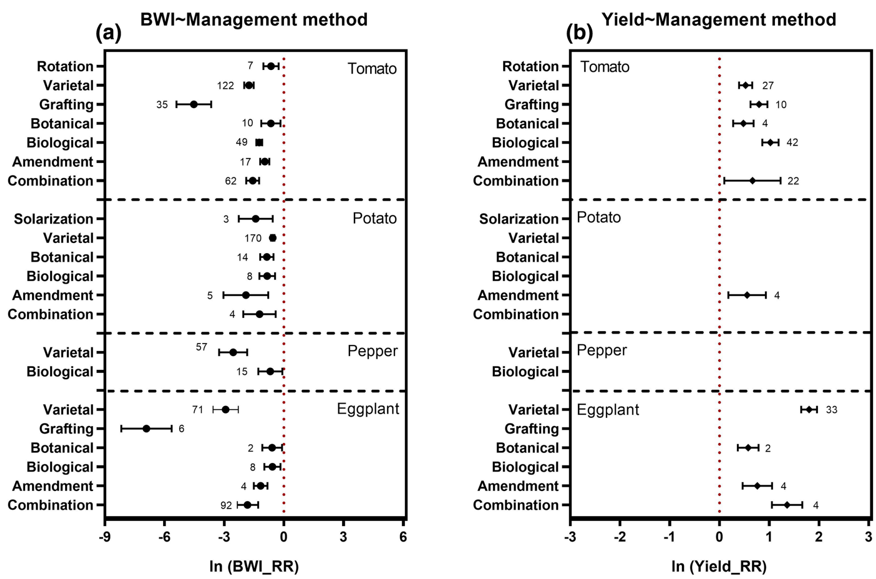


FIGURE 5 Bacterial wilt incidence (BWI) (a) and yield (b) response ratios (RR) as affected by individual agroecological management strategies and their combinations. Because of insufficient data, some modalities are not presented.



The BWI response ratios were not significantly affected by the treatment support for potato and eggplant (Figure 8a). However, on tomato and pepper, BWI response ratio was significantly higher when AEMS were applied on soil than plant. AEMS reduced the BWI more when applied directly on the plant than on the soil. For the crop yield response ratio, no significant difference was found for all crops regarding the treatment support (Figure 8b), except eggplant, for which applying AEMS to both plant and soil was significantly more effective than applying it to the soil only.

Across all AEMS, the BWI response ratio was significantly affected by the type of inoculation (natural or artificial) for pepper but not for tomato, potato and eggplant (Figure 9a). For pepper, AEMS were found to be more effective when RSSC was artificially inoculated compared to natural infection. On tomato, no significant difference was found for yield response ratio between natural and artificial RSSC inoculation (Figure 9b).

Analysis of the response ratio of BWI and yield revealed that the effectiveness of AEMS was not affected by the type (local or improved) of variety for tomato, eggplant and potato (Figure 10a), but for pepper, AEMS were more effective on improved varieties in terms of BWI response ratio. However, crop yield response ratio was higher on improved compared to local varieties for tomato and eggplant (Figure 10b). No data was found for pepper.

The BWI response ratio varied across different climatic areas. AEMS was significantly more effective in humid areas, resulting in a greater reduction of the BWI response ratio for tomato and potato (Figure 11a). For tomato, the BWI response ratio was higher in dry subhumid areas than in very humid or humid areas. Likewise, for

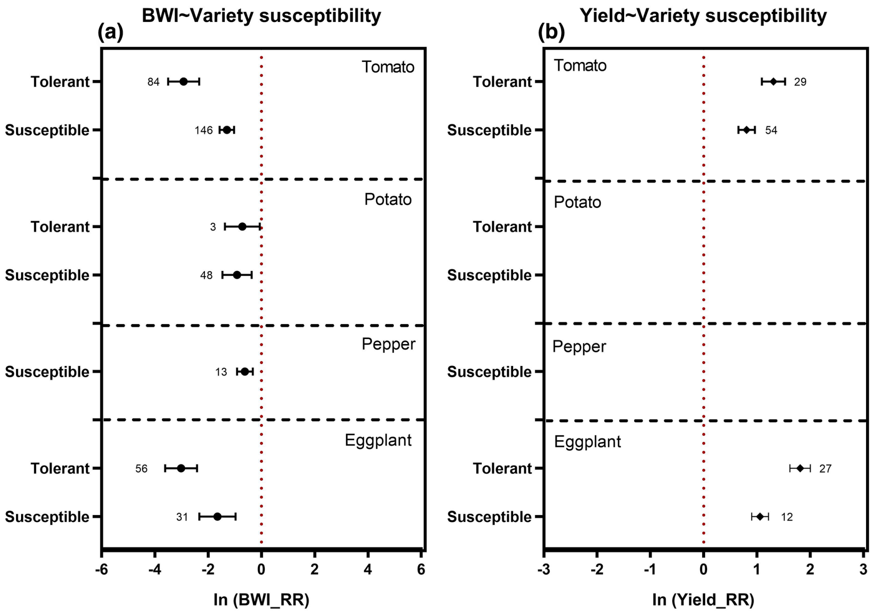


FIGURE 6 Bacterial wilt incidence (BWI) (a) and yield (b) response ratios (RR) as affected by crop variety susceptibility to *Ralstonia solanacearum* species complex. Because of insufficient data, some modalities (pepper BWI, potato and pepper yield) are not presented.

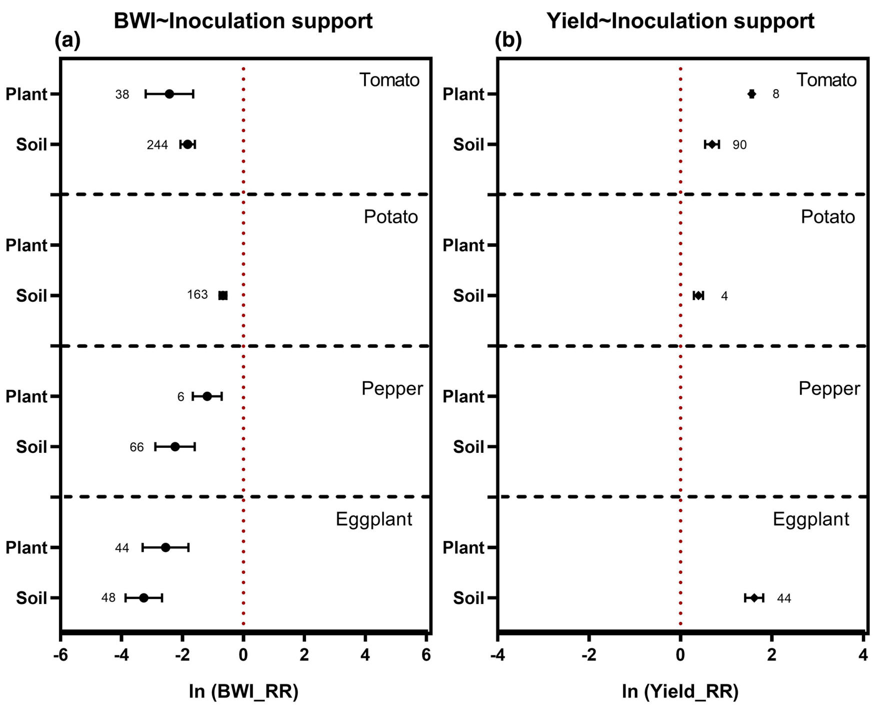


FIGURE 7 Bacterial wilt incidence (BWI) (a) and yield (b) response ratios (RR) as affected by the inoculation support of *Ralstonia solanacearum* species complex. No data for pepper yield.

potato, the BWI response ratio was higher in semi-arid areas than very humid and subhumid areas. There was no significant difference in the yield response ratio for tomatoes and eggplants across different climatic areas. Due to lack of data, the yield response ratio could not be determined for the arid climatic area (Figure 11b).

The BWI response ratio was significantly lower under strongly acidic soil for tomato and very strongly acidic soil for pepper compared to extremely acidic soil (Figure 12a). AEMS were significantly less effective under extremely acidic conditions for these crops but more effective than under very strong acidic soil for tomato. For potato and eggplant, no significant difference was found based on different levels of soil acidity. Similarly, the yield response ratio was lower for tomato and eggplant on extremely acidic soil than strongly and very strongly acidic soil (Figure 12b). No data was found for pepper.

4 | DISCUSSION

Agroecological pest management strategies against bacterial wilt disease in solanaceous crops have been widely studied on tomato, pepper, potato and eggplant. No data was found for African eggplant. This reveals a research gap on bacterial wilt management strategies for this crop which is mostly cultivated in Africa. Regarding the overall means by crop, potato showed a high BWI response ratio and lowest yield response ratio across all AEMS compared to eggplant,

FIGURE 8 Bacterial wilt incidence (BWI) (a) and yield (b) response ratios (RR) to agroecological management strategies as affected by treatment support. No data for pepper yield.

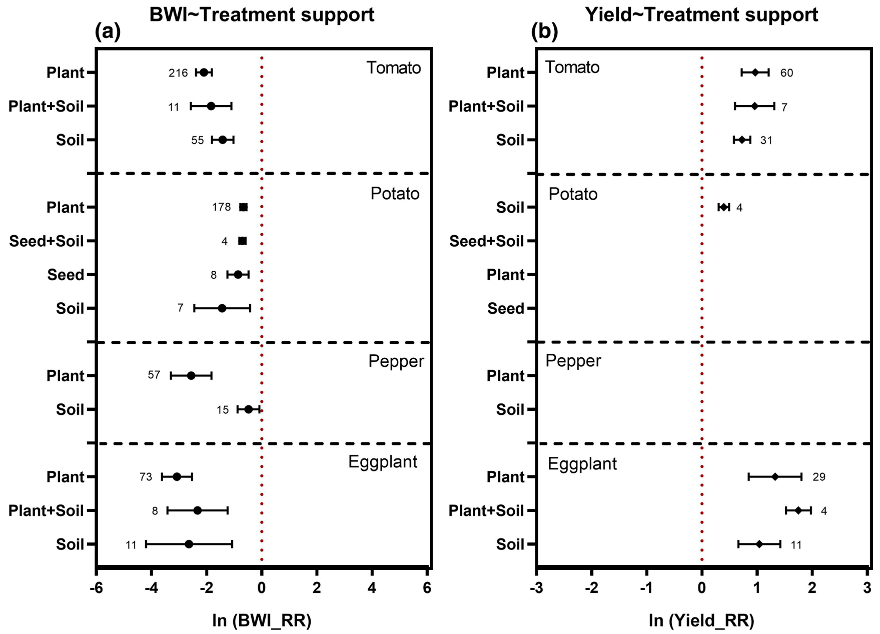
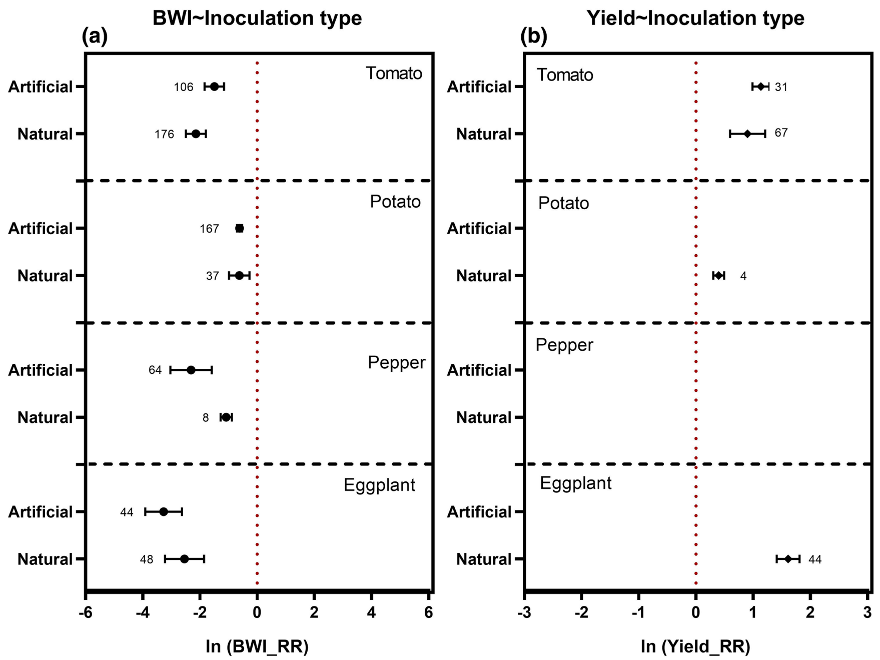


FIGURE 9 Bacterial wilt incidence (BWI) (a) and yield (b) response ratio (RR) to agroecological management strategies as affected by inoculation type. No data for pepper yield.



tomato and pepper. AEMS were less effective on potato crops than eggplant, tomato and pepper and yield losses were also higher on this crop. Potato tubers are both the consumable part of the crop and are directly affected by the pathogen, increasing susceptibility and yield losses. Likewise, the pathogen is seed transmitted with latent infection, which exacerbates yield losses (Okiro et al., 2024). In contrast, for crops like tomato, pepper and eggplant, only the roots are directly exposed to the pathogen. This result also suggests that potato is more susceptible to bacterial wilt caused by RSSC than eggplant, pepper and tomato.

Our results indicate that the performance of AEMS under on-station and on-farm conditions were not significantly different in terms of BWI for tomato, eggplant and pepper. Chandrasekaran et al. (2016), in their meta-analysis on the effectiveness of BCAs of bacterial wilt management, arrived at the same conclusion. Hence, in bacterial wilt management, the results obtained on-station can be directly transposed to on-farm conditions for these crops. For potato, management strategies appeared less effective on-station than on-farm. However, the reliability of the mean response ratio (and associated confidence interval) under on-station conditions may be questioned given the very low number of on-station observations for potato. Regarding crop yield, for tomato, AEMS increased yield more under on-station than on-farm conditions. This could be related to several other biotic factors such as other pests and diseases and abiotic

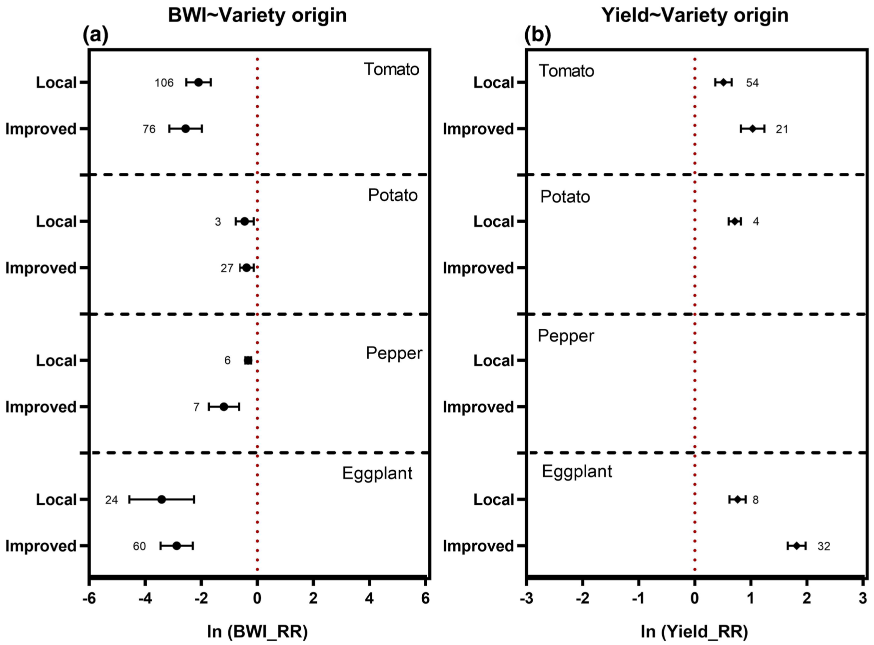


FIGURE 10 Bacterial wilt incidence (BWI) (a) and yield (b) response ratios to agroecological management strategies as affected by variety origin. No data for pepper yield.

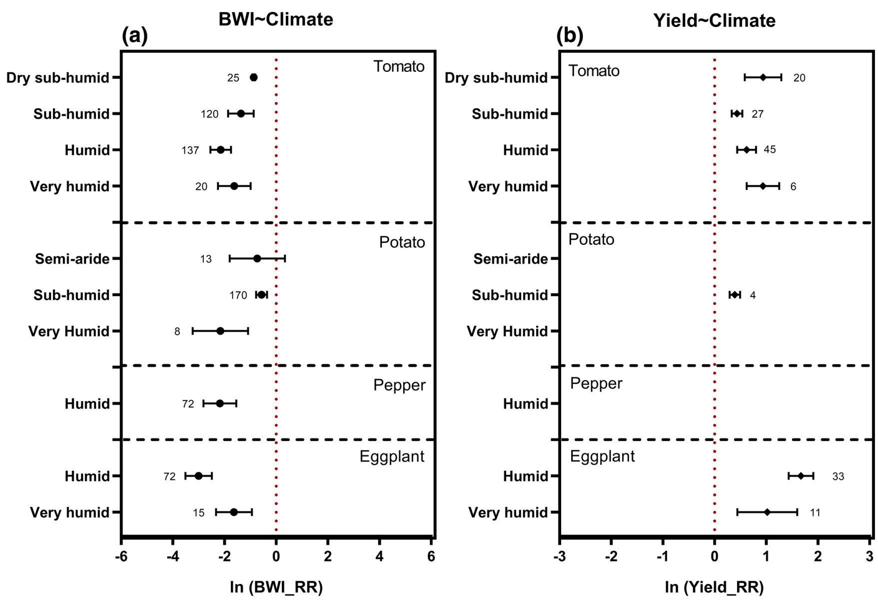


FIGURE 11 Bacterial wilt incidence (BWI) (a) and yield (b) response ratio (RR) to agroecological management strategies as a function of the climatic zone. No yield data for pepper crop and humid and arid areas.

conditions such as temperature and soil fertility that are less controllable under on-farm than on-station conditions and directly influence tomato yield. Because RSSC is widely distributed in tropical, subtropical and temperate areas (Osdaghi, 2020; Thakur et al., 2021), a wide variety of agroecological practices for its control have been tested under a wide range of conditions. Varietal control, biological control, botanical control, grafting with resistant rootstock, crop rotation, soil amendments, solarization and combinations of different management methods were used in bacterial wilt management on solanaceous crops to reduce BWI and yield loss on-farm and on-station, as also reported by Yuliar et al. (2015) in their review. The most reported AEMS were varietal control, biological control and combinations of management methods, while crop rotation and solarization were the least reported AEMS. This can be explained by the time required for testing the effect of crop rotation and achieving conclusive results, as well as the resources needed to treat soil (solarization). Likewise, Yuliar et al. (2015) also reported that intercropping methods and preventive methods such as keeping fields free of RSSC by using healthy seeds for potato or uncontaminated water and tools, have been little studied scientifically. These strategies are particularly important for maintaining soils free from infestation and preventing the spread of the pathogen, especially for potato, where RSSC is seed-transmitted.

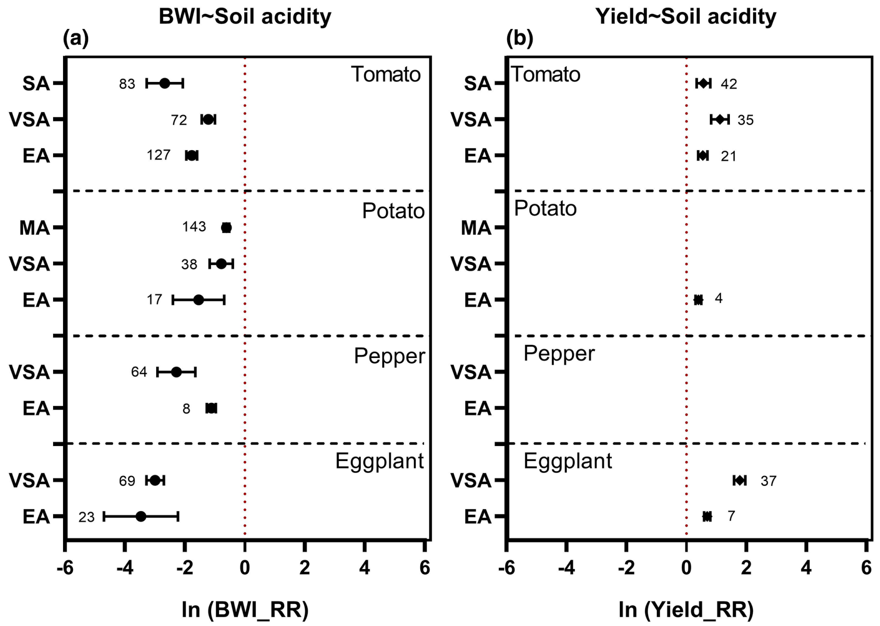


FIGURE 12 Bacterial wilt incidence (BWI) (a) and yield (b) response ratio (RR) as influenced by soil acidity. EA, extremely acidic; VSA, very strongly acidic; SA, strongly acidic; MA, moderately acidic. No data for pepper yield.

The efficiency of AEMS varied from one crop to another. This can be linked to the crop genetics, the disease transmission methods, the diversity of experimental conditions and the bacterial diversity. However, against bacterial wilt caused by RSSC, our results indicate that grafting of scions of a susceptible variety onto resistant rootstock is the most effective control method to reduce BWI for tomato and eggplant. The BWI response ratio of the grafting control method was more than three orders of magnitude more effective than other AEMS. However, it is important to note that the number of BWI response ratio observations on eggplant was only six. Many studies have recently reported grafting as highly effective in bacterial wilt management, even reducing BWI on tomato to 0% (Cardoso et al., 2012; Ganiyu et al., 2018, 2020; Kumbar et al., 2021). Mihajlovic et al. (2017), in their qualitative review, also reported grafting as highly effective in managing other soilborne diseases on tomato such as *Verticillium* spp., *Fusarium oxysporum*, *Phytophthora* spp. and *Meloidogyne* spp. These rootstocks can hinder the multiplication and spread of the bacteria once in the stem, thereby protecting the susceptible scion, which is consequently able to express its production potential (Nakaho et al., 2004). This strategy has been widely used in Japan, Korea and several European countries for many years (Louws et al., 2010). Unlike tomatoes, peppers and eggplants, the AEMS reported in this study all showed a similar reduction in BWI for potatoes.

Although grafting was the best method in terms of BWI for tomato and eggplant, the highest response ratio of yield was obtained with varietal control strategy and combinations of management methods for eggplant and biological control, grafting and combinations of management methods for tomato. In fact, grafting can reduce plant vigour as well as vegetative growth and yield compared to ungrafted plants (Rotino et al., 2005), although conflicting results have been reported in the literature. Indeed, Khah (2011) and Rivard et al. (2012) demonstrated a yield advantage with grafted plants compared to ungrafted plants. In their meta-analysis performed on 159 publications and 202 rootstocks, Grieneisen et al. (2018) concluded that 65% of observations did not show any difference in yield between grafted and ungrafted plants. Despite the risk of a lower yield when using grafted plants, in the management of devastating diseases such as bacterial wilt caused by RSSC, grafting can be an efficient management strategy because the yield losses recorded with grafting strategies were lower than those recorded using other control strategies on eggplant. This is probably the reason why this strategy is widely used in Asian countries like Korea and China. Likewise, in tomato production, despite varietal control showing the highest reductions of BWI response ratio compared to other AEMS, this strategy did not show the highest yield response ratio. In fact, tomato fruit size decreases with variety resistance to bacterial wilt caused by RSSC. Many studies have mentioned a negative correlation between the level of bacterial wilt resistance and agronomic performance such as yield (Opina et al., 1988; Walter, 1967; Zohoungbogbo et al., 2021), which can explain this counterperformance of the varietal control method in tomatoes.

In contrast to grafting and varietal control, combinations of management methods showed a moderate performance in reducing BWI and a higher yield than other strategies for tomato and eggplant. Indeed, combinations of many control strategies can be more beneficial in terms of synergy for plants, especially when increasing soil quality and plant nutrition, which helps improve yield. Combinations of many management methods such as varietal control, rotation or soil amendments have been reported to effectively reduce BWI and increase yield compared to the control (Adhikari & Basnyat, 1998; Alfano et al., 2011; Sharma & Kumar, 2000; Vinh et al., 2005).

As expected, for tomato and eggplant, AEMS were more effective on tolerant varieties than on susceptible varieties for both BWI and yield response ratio. However, for potato, the BWI response ratio was not significantly different between susceptible and tolerant varieties. This can be explained by the fact that, even when a potato cultivar is classified as resistant, it can transmit a latent infection to its progeny through infested seed (French et al., 1998; Muthoni, 2014). In addition, the edible part of the potato plant is also directly affected by the pathogen, increasing yield losses compared to above-ground fruit crops such as tomato and eggplant. However, regardless of whether the management strategy is applied on plant, soil, or plant and soil, no difference was found for the BWI response ratio for tomato, eggplant and potato, in contrast to pepper, where AEMS were significantly more effective when applied on plant than soil.

While the mean BWI on the untreated controls was 93.86%, 71.2% and 74.49% in dry subhumid, humid and arid areas, respectively, these means were 38.52%, 30.67% and 37.21% after applying AEMS. The BWI response ratio demonstrated that AEMS were more effective in humid than arid areas for tomato and potato. In fact, some of these AEMS like soil amendment, biological control and botanical control are based on improving the physical, chemical and microbial quality of soils in order to promote competition, parasitism and symbiotic relationships, which result in better plant nutrition. Unfortunately, in arid areas, Bernhard et al. (2018) showed low microbial abundance compared to humid zones, as hard environmental conditions favour only microorganisms that are highly adapted and able to cope with these conditions. Furthermore, especially for AEMS like varietal control and grafting, plant tolerance or resistance to RSSC is weakened when temperatures are high, as in arid areas, compared to humid areas where they are generally moderate (Dossoumou et al., 2021). Singh et al. (2014) showed that tomato cultivars are more susceptible to RSSC at 35°C than at 20°C. However, for potato and pepper, no significant difference was found regarding climatic area.

Finally, our results indicate that AEMS for bacterial wilt control were more effective in reducing BWI in very strongly acidic (VSA) and strongly acidic (SA) soils than extremely acidic (EA) soils on pepper and tomato, respectively. The same trend of increasing yield was also recorded for tomato and eggplant. Tafesse et al. (2021) showed that BWI increased with soil acidity. Li et al. (2017) came to the same conclusion that soil acidification aggravated occurrence, incidence and severity of bacterial wilt by inhibiting development of antagonist bacteria such as *Bacillus cereus* and *P. fluorescens*. In addition, nutrient availability is limited for plants in highly acidic soils, making them more prone to diseases (Tripathi et al., 2022). In such cases, AEMS may be less effective in reducing BWI and increasing yield.

It should be noted that the results of this study have some limitations due the low number of observations of some variables analysed. In addition, pH data was collected from SoilGrid and is therefore predicted data only.

5 | CONCLUSION

Agroecological management strategies substantially reduce BWI and increase yield compared to the untreated control in tomato, pepper, potato and eggplant. These strategies are widely used on all continents where RSSC occurs. Our meta-analysis revealed that among multiple agroecological bacterial wilt management practices tested under on-station and on-farm conditions, grafting is the best control method to reduce BWI in tomato and eggplant. On pepper, varietal control outperformed biological control. Conversely, for potato, all AEMS showed similar performance in reducing BWI. However, AEMS that achieved a high reduction of BWI did not always show the highest yield. For tomato, biological control, combinations of management methods and grafting showed the best yield, whereas it was combinations of management methods and grafting for eggplant. AEMS effectiveness varies with many factors such as type of crops, variety used, support where AEMS are applied, inoculation method, climatic zone and soil acidity. Therefore, it is necessary to carry out site-specific control for effective and agroecological management of bacterial wilt caused by RSSC on these crops.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were generated.

ORCID

Moukaïla Bagri Bouraïma https://orcid.org/0009-0008-4337-9942
Enoch G. Achigan-Dako https://orcid.org/0000-0002-5493-0516

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