Biological seed treatments promote crop establishment and yield: a global meta-analysis

Jay Ram Lamichhane, David Corrales, Elias Soltani

Agronomy for Sustainable Development (2022) 42:45
https://doi.org/10.1007/s13593-022-00761-z

META-ANALYSIS

Biological seed treatments promote crop establishment and yield: a global meta-analysis

Jay Ram Lamichhane [1] · David Camilo Corrales [1] · Elias Soltani [2]

Accepted: 31 January 2022

Abstract
Seeds are a vector of genetic progress and, as such, they play a significant role in the sustainability of the agri-food system. The current global seed market is worth USD 60 billion that is expected to reach USD 80 billion by 2025. Seeds are most often treated before their planting with both chemical and biological agents/products to secure good seed quality and high yield by reducing or preventing losses caused by diseases. There is increasing interest in biological seed treatments as alternatives to chemical seed treatments as the latter have several negative human health and environmental impacts. However, no study has yet quantified the effectiveness of biological seed treatments to enhance crop performance and yield. Our meta-analysis encompassing 396 studies worldwide reveals for the first time that biological seed treatments significantly improve seed germination (7±6%), seedling emergence (91±5%), plant biomass (53±5%), disease control (55±1%), and crop yield (21±2%) compared to untreated seeds across contrasted crop groups, target pathogens, climatic regions, and experimental conditions. We conclude that biological seed treatments may represent a sustainable solution to feed the increasing global populations while avoiding negative effects on human health and ensuring environmental sustainability.

Keywords Non-chemical seed treatment · Seed germination · Seedling emergence · Soil-borne pathogens · Sustainability

1 Introduction

Crop losses due to pests (*sensu lato* that includes animal pests, pathogens, and weeds) may range from 50 to more than 80% (Oerke 2006) and those caused by crop pathogens alone cost the global economy USD220 billion annually (Savary et al. 2019). These losses may be prevented or contained by applying effective crop protection measures. Chemical pesticides are the most commonly used crop protection measures, from pre-sowing to post-harvesting (Oerke 2006; Cooper and Dobson 2007; Aktar et al. 2009). More specifically to seed treatments, chemical seed treatments are generally aimed at controlling seed- and soil-borne pests affecting crop establishment (Figure 1), crop biomass development, and yields (Wrather et al. 2010; Simpson et al. 2011; Munkvold et al. 2014; Sappington et al. 2018; Lamichhane et al. 2020b; Hitaj et al. 2020).

The routine-based planting of chemically treated seeds has raised several socio-economic, human health, and environmental concerns. This is because of the poor efficacy or inconsistent effectiveness of chemical seed treatments in controlling seed- and soil-borne pests (Rossman et al. 2018; Mourtzinis et al. 2019; Lundin et al. 2020; You et al. 2020; Fadel Sartori et al. 2020); risk exposure to operators that treat seeds or handle treated seeds (White and Hoppin 2004; Han et al. 2021); development of different forms of human cancer (AGRICAN 2020); and negative effects on non-target organisms such as bees (Rundlof et al. 2015; Main et al. 2020), birds (Li et al. 2020b; Fernández-Vizcaíno et al. 2021), and soil beneficial microorganisms (Nettles et al. 2016; Zaller et al. 2016; Gomes et al. 2017). In addition, the planting of chemically treated seeds negatively affects beneficial plant fungal endophytes, involved in plant growth and development thereby reducing early plant growth (Vasanthakumari et al. 2019).

✉ Jay Ram Lamichhane
jay-ram.lamichhane@inrae.fr

✉ Elias Soltani
elias.soltani@ut.ac.ir

[1] INRAE, Université Fédérale de Toulouse, UMR AGIR, F-31326 Castanet-Tolosan Cedex, France

[2] Department of Agronomy and Plant Breeding Sciences, College of Aburaihan, University of Tehran, Pakdasht, Tehran, Iran

Published online: 23 May 2022

Fig. 1 Damping-off and root rot of soybean caused by *Pythium* spp. Poor seedling emergence and post-emergence seedling death leading to a low quality of crop establishment and stand development are an indicator of these diseases. Seed treatments represent an important practice to protect the seed and seedlings both pre- and post-emergence. In fields with historical problems of soil-borne pathogens, seed treatments represent an important agronomic lever to enhance germination and emergence vigor (i.e., the speed of seed germination and seedling emergence) that is essential for plant development and yield. Photo courtesy of Tom Allen, Mississippi State University, USA.

Therefore, there is a need to limit or replace chemical seed treatments with other sustainable practices to achieve the same goal — viz. improved seed germination, seedling emergence, biomass production, pest control, and crop yield — with no or reduced human health and environmental impacts (Lamichhane 2020).

Biological seed treatments contain active ingredients encompassing microbes like fungi and bacteria, as well as plant and algae extracts. Previous studies investigated the effectiveness of biological seed treatments in controlling seed- and soil-borne pests including their potential to improve seed germination, seedling emergence, plant biomass development, and yield (see the list of references used in the meta-analysis). However, the type of product used for biological seed treatments, the target seed- and soil-borne pests, the climate zone, the crop group, and the experimental conditions considered in these studies are very heterogeneous. Consequently, the effectiveness of a given biological seed treatment may significantly vary across contrasted systems or conditions and, therefore, the results of individual studies are not sufficient to draw a general conclusion. Quantitative systematic review or meta-analysis is particularly useful in quantifying and synthesizing the potential of biological seed treatments on crop development and yield. Enhanced knowledge on the best performing biological seed treatments across different crop species or different environmental gradients will be instrumental in the adoption of planting biologically treated seeds. This will in turn save yields needed to feed the increasing world population while reducing environmental risk and health hazards. Several recent meta-analyses in the field of agronomy successfully quantified the impact of different cropping practices on crop development and yield (Soltani and Soltani 2015; Carrillo-Reche et al. 2018; Knapp and van der Heijden 2018; Li et al. 2020a, c). In contrast, to the best of our knowledge, no meta-analysis has been performed yet to quantify the effectiveness biological seed treatments on crop performance and yield.

The objective of this study was to quantify, via a meta-analysis, the effectiveness of biological seed treatments in improving seed germination, seedling emergence, plant biomass development, disease control, and yield compared to untreated seeds (i.e., without application of any chemical or biological products) across contrasted environmental conditions, crop groups, and climate zones.

2 Materials and methods

2.1 Data sources

Data for the meta-analysis were retrieved from the ISI-Web of Science database taking into account articles published before 11 June 2020. The keywords used to find the articles were "non-chemical seed treatment" (68 publications), "biological seed treatment" (140 publications), "seed bacterization (366 publications), and "seed treatment" (3284 publications). Only the studies that compared biological seed treatments vs. untreated seeds and their effect on the following five variables — viz. seed germination (SG), seedling emergence (SE), plant biomass (PB), disease control (DC; either disease incidence or severity) or crop yield (CY) — were included in the meta-analysis. Although CY is the key final output of interest, we also focused on other four response variables for two main reasons. First, given that we included all crop groups in our meta-analysis, the definition of the response variable CY differs between cereals (the quantity of the harvested grain per unit surface) and vegetables (the quantity of the harvested biomass per unit surface that could be sprouts or leaves used such as ready-to-use leafy vegetables). Second, the potential of biological seed treatments to improve crop performance is mainly due to an improved control of seed- and soil-borne pests that affect the early crop development phase (SG & SE etc).

We did not consider those studies where seed treatments were applied to break seed dormancy or to control weeds. Conference papers or book series were also excluded especially if they were not available online or did not contain a full text. Overall, 64 articles were selected for seed germination, 126 articles for seedling emergence, 153 articles for plant biomass, 210 articles for disease development, and 163 articles for crop yield (Supplementary Data 3). The mean values and the number of replications/observations for the selected characteristics were extracted from the selected articles. For studies that consisted of a series of experiments, different biological seed treatments or different environmental conditions, each comparison between biological seed treatments and the control treatments was considered as a separate data point ("observation").

2.2 Data set overview

The selected articles contained 8596 observations. Most of these articles tested biological seed treatments under several sets of experiments and had a high weighted data. DC was investigated in about 34.5% of the total observations followed by SE (24.6%), PB (17.6%), CY (14.6%), and SG (8.8%).

Experiments were conducted either under controlled or field conditions. Experiments performed under controlled conditions included those on SG and PB measurements. SE data were measured either in studies conducted under controlled conditions (48% of data) or those carried out under field conditions (52% of data). Likewise, 42% and 58% of the data on DC were measured under controlled and field conditions, respectively. Most of the data on CY were obtained under field conditions (82%) while the rest (18%) were collected under controlled conditions. Field experiments were conducted across South and North America, Europe, North Africa and Asia under different climate zones. Key information concerning crop or crop group, the target biotic stress, and the measured variables are presented in Supplementary Data 3.

In the selected articles for meta-analysis, plant pathogenic fungi were the key target of biological seed treatments (58%) followed by oomycetes (11%), bacteria (8%), nematodes (3%), and viruses (3%). Some studies also considered a pathogen complex that involved more than one pathogen at the same time (e.g., under field conditions) which included 13% of the data. In experiments conducted under controlled conditions, seeds/soils were either artificially inoculated or not with one or more pathogens. Non-inoculated treatments (i.e., control) were also considered which contained 4% of the data. We did not consider the potential effect of biological seed treatments on insect pest control as only little information is available on this topic in the literature.

2.3 Data analysis

In each study and for each data point, the response ratio (R) was calculated to detect the effects of biological seed treatments on the five response variables as follows (Marty and BassiriRad 2014):

$$R = \left(\frac{\overline{X}_t}{\overline{X}_c}\right) \quad (1)$$

where $\overline{X}_t$ and $\overline{X}_c$ are the mean values for measured plant traits subjected to biological seed treatments and control (untreated seeds), respectively. Standard error (SE) was estimated for each n observations as shown below (Neyeloff et al. 2012):

$$SE = \frac{R}{\sqrt{R \times n}} \quad (2)$$

The weighted average has a desirable feature as it gives more weight for studies with a higher number of observations compared with those with a lower number of observations. This provides an appropriate way to calculate the overall effect size (Gurevitch and Hedges 1999). The weight for each observation (w_v) was calculated as below:

$$w_v = \frac{1}{(SE^2 + v)} \quad (3)$$

where v is a constant that represents variability due to sampling error as well as variability in the population of effects and can be calculated as follows (Neyeloff et al. 2012):

$$v = \frac{Q-(k-1)}{\sum w - \left(\frac{\sum w^2}{\sum w}\right)} \quad (4)$$

where k is number of observations, w is equal to $\frac{1}{SE^2}$ and Q is heterogeneity among observations (see the section 2.4 for its calculation).

Weighted average of the response ratio ($\overline{R}$) was calculated as follows (Neyeloff et al. 2012):

$$\overline{R} = \frac{\sum(w_v \times R)}{\sum w_v} \quad (5)$$

Heat map graphs were used to show the differences among study factors for $\overline{R}$. The weighted average of the response ratio >1 in the heat map indicates a positive response while a value of <1 shows a negative response. Standard error of $\overline{R}$ ($SE_{\overline{R}}$) was estimated as shown below (Neyeloff et al. 2012) :

$$SE_{\overline{R}} = \sqrt{\frac{1}{\sum w_v}} \quad (6)$$

Significant changes were tested by 95% confidence intervals (CI), which were calculated as follows (Neyeloff et al. 2012):

$$CI = \overline{R} \pm 1.96 \times SE_{\overline{R}} \quad (7)$$

No overlap of confidence intervals with zero indicates that biological seed treatments significantly affected the measured plant traits.

For easier interpretation of the results, the percentage of change due to biological seed treatments compared with the control was calculated (changes (%)) for all the measured plant traits as follows (Hedges et al. 1999; Marty and BassiriRad 2014; Soltani et al. 2018):

$$\text{Changes }(\%) = \left[\overline{R}-1\right] \times 100 \tag{8}$$

where a positive and a negative percentage change value indicates an increase and a decrease of the measured trait, respectively. For example, for disease development, a negative value shows a reduction in disease development (i.e., a better disease control).

2.4 Heterogeneity test

The heterogeneity among the effect sizes of studies was tested using a chi square (Q) test and I^2 statistic to determine whether the variance among effect sizes was significantly greater than the expected sampling error (Rosenberg et al. 2004). A significant Q value shows that a portion of the heterogeneity can be explained by subgrouping the studies into different categories (Traveset and Verdu 2002; Rosenberg et al. 2004; Soltani et al. 2018). Both fixed- and random-effects were calculated to determine the heterogeneity in different studies (Neyeloff et al. 2012). However, a random-effect is more suitable than a fixed-effect in our meta-analysis. This is because the data used came from a series of individual studies that were performed across different crop groups, biological seed treatment types, and climate zones. Therefore, it is unlikely that all the studies were functionally equivalent. Therefore, Q values were calculated as follows (Neyeloff et al. 2012):

$$Q = \sum\left(w \times R^2\right) - \frac{\left[\sum(w \times R)\right]^2}{\sum w} \tag{9}$$

The calculated Q shows random-effects (Q_v) if we use w_v instead of w in Eq. (9). Finally, I^2 statistics were calculated as suggested previously (Neyeloff et al. 2012):

$$I^2 = \frac{(Q - df)}{Q} \tag{10}$$

where I^2 indicates the heterogeneity due to the random-effects if we use Q_v and df is equal to k-1. I^2 ranges between 0 and 100%. The heterogeneity is not important when $I^2 < 40\%$, moderate when $30\% < I^2 < 60\%$, substantial when $50\% < I^2 < 90\%$, and considerable when $75\% < I^2 < 100\%$.

2.5 Mean effect size by study factor

Study factors were categorized into six different subgroups to further investigate the effect of biological seed treatments on the response variables and mean effect sizes were calculated for each subgroup. The first subgroup was « experimental conditions » that included a comparison of controlled vs. field conditions and their combination. Controlled conditions consist of experiments conducted in growth chambers, greenhouses, and tunnels. The second subgroup was « biological seed treatments» that comprised seed treatments with plant extracts (PE), plant derived products (PDP), or microorganisms (M). The latter included either bacteria or fungi as a subgroup. The third subgroup was « crop groups » which included cereals, horticultural, industrial, or leguminous crops. The forth subgroup was « the target biotic stress » including plant pathogenic fungi, oomycetes, bacteria, nematodes, viruses, a pathogen complex, or no biotic stress conditions (i.e., negative control). The situation of pathogen complex includes more than one type of biotic stress that often occur under field conditions (Lamichhane and Venturi 2015; Rojas et al. 2016; van Agtmaal et al. 2017; You et al. 2020). The fifth subgroup was « climate zones » based on the zone of field studies considered in the meta-analysis, which were tropical, arid, temperate climate with no dry season (NDS), temperate climate with dry season (DS), or continental climate (C). The climate zones were determined using an online search of the location of the study on the website (https://en.climate-data.org/). The differences between subgrouped categories were considered significant if their confidence intervals did not overlap.

3 Results and discussion

3.1 Heterogeneity test

The Q test was significant for all response variables except for CY showing that a portion of the heterogeneity can be explained by subgrouping the studies into different categories. In contrast, the Q_v tests indicated that the heterogeneity of SG ($Q_v = 47.2$) and CY ($Q_v = 498.9$) was not significant (Table 1). Using the fixed-effects, I^2 statistic showed considerable heterogeneity for all response variables except for CY. When I^2 statistics were calculated as random-effect, the heterogeneity was not important for SG, DC, and CY while substantial heterogeneity was found for SE and PB (Table 1). Therefore, we used Q_v for further analysis to calculate $\overline{R}$. Subgrouping of the studies into different categories allowed us to reduce the heterogeneity of the data in some cases (Tables 2 and 3). For example, the heterogeneity of SE data was low and non-significant under tropical and arid climates (Table 2).

3.2 Overall effectiveness of biological seed treatments

Overall, when all study factors were combined, biological seed treatments significantly improved SG (7±6%) and SE (91±5%) compared with the untreated seeds (Fig. 2a). The gain in SE due to the planting of biologically treated seeds

Table 1 Heterogeneity among the effect sizes of studies. The heterogeneity was calculated by chi square (Q) and I^2 tests taking into account both fixed- and random-effects for the response variables. SG, seed germination; SE, seedling emergence; PB, plant biomass; DC, disease control; CY, crop yield. **significant at p<0.01; ns, not significant.

Response variable	No. study	No. observation	Q Fixed	Random	I^2 Fixed	Random
SG	64	754	4767.54**	47.21^{ns}	84.21	0
SE	126	2114	38343.67**	16226.15**	94.50	86.98
PB	153	1509	9040.04**	5449.26**	83.32	72.33
DC	210	2964	11887.13**	3301.37**	75.07	10.25
CY	163	1255	877.33^{ns}	498.99^{ns}	0	0

was much higher under controlled conditions (123±8%) compared with that under field conditions (56±6%). Likewise, biological seed treatments significantly improved PB (53 ±5%) and DC (55±1%) compared with the untreated seeds (Fig. 2a). Disease control efficacy due to biological seed treatments was significantly different both under controlled (59

Table 2 Heterogeneity among different study factors and response variables as calculated by random-effects chi square (Q_W) tests. SG, seed germination; SE, seedling emergence; PB, plant biomass; DC, disease control; CY, crop yield; df, degree of freedom; PDP, plant derived products; PE, plant extracts; M, microorganisms; –, no data were available for the analysis; NDS, temperate climate with no dry season; DS, temperate climate with dry season; **p < 0.01; *p < 0.05; ns, not significant.

Groups	SG Df	Q_v	SE Df	Q_v	PB Df	Q_v	DC Df	Q_v	CY Df	Q_v
Experimental conditions										
Controlled	–	–	1021	11369.6**	–	–	1728	2358.1**	220	127.9^{ns}
Field	–	–	1091	5046.5**	–	–	1232	779.5^{ns}	1033	933.6^{ns}
Climate zones										
Tropical	–	–	26	26.3^{ns}	–	–	221	156.5^{ns}	101	101.5^{ns}
Arid	–	–	53	9.3^{ns}	–	–	338	303.2^{ns}	251	99.5^{ns}
Temperate NDS	–	–	26	630.2**	–	–	215	134.8^{ns}	238	223.7^{ns}
Temperate DS	–	–	45	94.4**	–	–	140	94.3^{ns}	135	214.8**
Continental	–	–	506	3325.0**	–	–	211	131.4^{ns}	254	220.9^{ns}
Crop groups										
Cereal	404	68.8^{ns}	441	797.1**	561	3779.9**	986	2065.6**	520	225.4^{ns}
Horticultural	348	31.7 ^{ns}	611	9956.9**	403	154.7^{ns}	917	507.9^{ns}	170	55.3^{ns}
Industrial	17	5.8^{ns}	297	2020.2**	182	227.5*	289	187.8^{ns}	135	51.87^{ns}
Leguminous	195	54.2^{ns}	758	3293.4**	357	472.4**	766	407.2^{ns}	425	429.6^{ns}
Biotic stresses										
Control	527	27.7^{ns}	361	81.4^{ns}	549	540.0^{ns}	118	88.7^{ns}	194	120.3^{ns}
Complex	7	0.1^{ns}	325	603.9**	66	90.0*	358	257.4^{ns}	194	201.6^{ns}
Fungi	195	41.7^{ns}	722	2474.4**	354	2633.6**	1647	2436.9**	394	415.4^{ns}
Bacteria	–	–	14	4.4^{ns}	19	26.6^{ns}	231	177.6^{ns}	–	–
Oomycetes	–	–	603	11963.5**	165	197.4*	309	296.1^{ns}	24	22.7^{ns}
Nematode	–	–	–	–	47	66.0*	93	97.1^{ns}	56	11.5^{ns}
Virus	–	–	–	–	–	–	73	75.0^{ns}	–	–
Seed treatments										
PDP	32	1.6^{ns}	90	201.7**	15	16.6^{ns}	111	528.5**	24	3.2^{ns}
PE	205	35.9^{ns}	173	186.1^{ns}	39	44.2^{ns}	134	65.7^{ns}	13	4.5^{ns}
M	514	36.3^{ns}	1848	15709.6**	1452	5349.4**	2714	1946.7^{ns}	1214	431.5^{ns}
Bacteria	380	92.2^{ns}	1012	8152.7**	1184	4955.5**	1806	1263.1^{ns}	932	841.6^{ns}
Fungi	128	14.1^{ns}	740	6222.0**	222	256.2^{ns}	795	561.6^{ns}	217	111.9^{ns}

Table 3 Heterogeneity among different study factors and response variables as calculated by random-effects chi square (Q_W) tests. SG, seed germination; SE, seedling emergence; PB, plant biomass; DC, disease control; CY, crop yield; df, degree of freedom; –, no data were available for the analysis; **p < 0.01; *p < 0.05; ns, not significant.

Groups	SG Df	Q_v	SE Df	Q_v	PB Df	Q_v	DC Df	Q_v	CY Df	Q_v
Key groups of bacteria										
Azospirillum spp.	19	0.9^{ns}	–	–	17	10.3^{ns}	–	–	19	0.8^{ns}
Bacillus spp.	105	7.2^{ns}	277	276.1^{ns}	286	491.2**	380	189.9^{ns}	237	162.8^{ns}
Burkholderia spp.	–	–	89	649.1**	106	111.5^{ns}	47	0.5^{ns}	17	19.5^{ns}
Paenibacillus spp.	–	–	17	23.8^{ns}	9	0.3^{ns}	–	–	9	11.1^{ns}
Pseudomonas spp.	151	68.3^{ns}	318	1720.5**	503	504.0^{ns}	961	800.1^{ns}	446	445.1^{ns}
Rhizobium spp.	–	–	36	39.1^{ns}	8	10.0^{ns}	30	10.1^{ns}	26	13.9^{ns}
Serratia spp.	25	2.3^{ns}	–	–	10	11.1^{ns}	33	30.4^{ns}	14	10.3^{ns}
Streptomyces spp.	–	–	30	118.7**	27	35.2^{ns}	39	37.4^{ns}	–	–
Key groups of fungi										
Clonostachys spp.	–	–	36	239.6**	–	–	12	18.9^{ns}	–	–
Gliocladium spp.	–	–	73	421.7**	–	–	78	84.8^{ns}	14	16.3^{ns}
Penicillium spp.	–	–	24	18.8^{ns}	22	28.6^{ns}	22	16.1^{ns}	6	1.4^{ns}
Trichoderma spp.	98	10.9^{ns}	567	5219.8**	122	140.7^{ns}	474	293.8^{ns}	166	125.0^{ns}

±1%) and field (48±2%) conditions. Biological seed treatments had significant impact on CY (21±2%) compared with the untreated seeds (Fig. 2a). CY improvement due to biological seed treatments was much higher under controlled conditions (18±6%) than that under field conditions (6±2%). For all the five response variables, the improvement due to biological seed treatments was more pronounced under controlled conditions compared with that under field conditions (Fig. 3).

The planting of biologically treated seeds systematically provided higher benefits under controlled conditions than in the field. This is not surprising as the efficacy of any seed treatment is reduced under field conditions due to a myriad of abiotic and biotic factors that interact under these conditions (Lamichhane et al. 2018, 2020a). However, our meta-analysis clearly shows that the planting of biologically treated seeds has a huge potential to enhance yield gain and to increase profitability even under field conditions due to improved disease control.

Compared with other variables, SE benefitted the most due to the planting of biologically treated seeds. This improved SE was mainly due to an enhanced level of control of diseases caused by soil-borne pathogenic fungi and oomycetes (Rojas et al. 2016; Foster et al. 2017; Serrano and Robertson 2018). While biological seed treatments enhanced SE via better control of individual plant pathogenic oomycetes and fungi, SE was improved to a lower extent in situations characterized by the pathogen complex. This means that, biological seed treatments are effective in controlling individual pathogens, but less effective against a disease complex involving different pathogens as shown previously (You et al. 2020).

3.3 Biological seed treatment types

Among different products used for biological seed treatments, seeds treated with M significantly improved SG (9±7%) compared with other products (Fig. 2b). No significant effect of seeds treated with fungal microorganisms was found on SG (p= 0.05) while biological seed treatments with beneficial bacteria significantly enhanced SG (7±4%). Both PDP and PE slightly improved SG but without any significant difference compared with other biological seed treatments (Fig. 2b).

Among the response variables, SE had the highest response ratios due to biological seed treatments (Fig. 3). Seed treatment with M was the most effective in improving SE (102 ±6%) compared with those with PE (7±6%) and PDP (21 ±15%; Fig. 2b). Both bacterial and fungal microorganisms used for seed treatments improved SE compared with untreated seeds, with fungal microorganisms being more effective (133±13%) than their bacterial counterparts (85±6%).

Significant increase in PB was found with seed treated with PE (37±13%) and M (54±6%) while seed treated with PDP did not have any significant impact on PB (13±23%) (Fig. 2b). Both bacterial and fungal microorganisms used for biological seed treatments significantly improved (p<0.05) PB by 56% and 38%, respectively.

All sub-grouped products used for biological seed treatments significantly provided (p<0.05) a more effective DC with significant difference in their effectiveness (Fig. 2b). The magnitude of DC obtained was similar between seed treated with M (52±1%) and PE (53±7%) while DC was significantly higher with seeds that were treated with PDP (75 ±3%). Biological seed treatments with beneficial fungi or

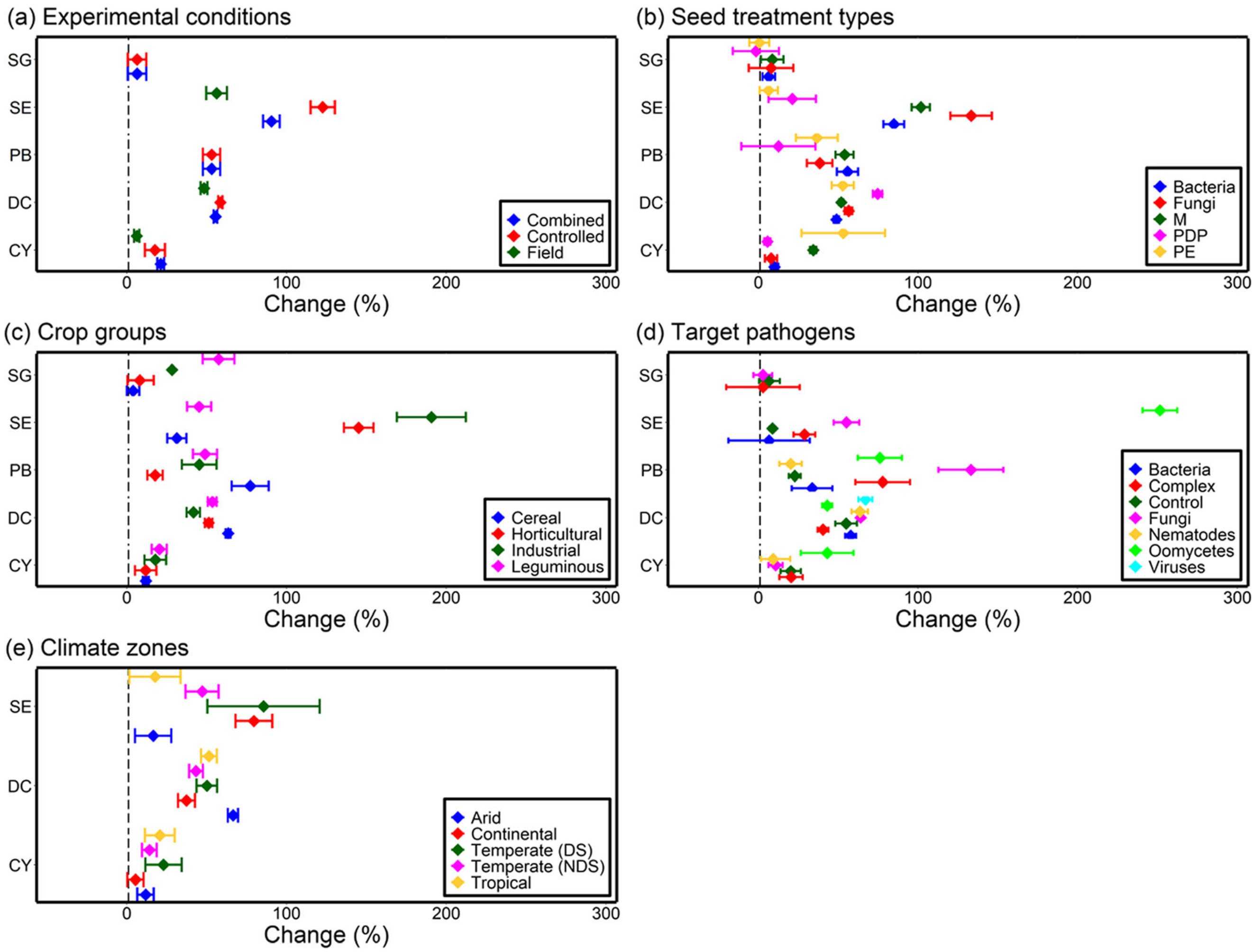

Fig. 2 Changes (%) in response variables due to biological seed treatments compared with untreated seeds (i.e., control; see Eq. 8 for detailed information). The changes are grouped by experimental conditions (**a**), seed treatment types (**b**), crop groups (**c**), target pathogens (**d**), and climate zones (**e**). Error bars show 95% confidence intervals (CI). No overlap of error bars with zero indicates that biological treatments significantly affected the response variables. Differences among sub-group categories are not significant when error bars are overlapped. No error bars indicate that the symbol is larger than the error. SG, seed germination; SE, seedling emergence; PB, plant biomass; DC, disease control; CY, crop yield; PDP, plant derived products; PE, plant extracts; M, microorganisms; NDS, temperate climate with no dry season; DS, temperate climate with dry season. The number of studies and observations for each response variable is reported in Table 1.

bacteria provided DC to a similar extent (fungi +57% vs. bacteria +49%) while their effectiveness was significantly different ($p<0.05$) compared with untreated seeds (Fig. 2b).

Commonly used microorganisms (bacteria and fungi) for seed treatments and their response values are listed in Table S1. Likewise, the most effective bacteria and fungi in improving crop performance and yield, when applied with seed treatments, are reported in Fig. 4 a and b, respectively. All response variables but SG were significantly improved when bacteria or fungi were used for seed treatments.

Among bacteria (Fig. 4a), seed treatments with *Burkholderia* spp. were the most effective in terms of improved SE (180±38%) followed by those with *Paenibacillus* spp. (115 ±63%), *Pseudomonas* spp. (82±13%), *Rhizobium* spp. (59 ±20%), and *Bacillus* spp. (10±4%). No significant change in PB was observed when seeds were treated with *Azospirillum* spp. while *Rhizobium* spp. (66±57%) followed by *Streptomyces* spp. (53±35%), *Bacillus* spp. (36±8%), *Pseudomonas* spp. (27 ±4%), *Paenibacillus* spp. (21±16%), *Burkholderia* spp. (19 ±7%), and *Serratia* spp. (18±13%) seed treatments significantly enhanced PB, in decreasing order of importance. All but *Burkholderia* spp. provided significant DC with *Serratia* spp. (68±7%) being the most effective, followed by *Streptomyces* spp. (51±9%), *Bacillus* spp. (49±4%), *Pseudomonas* spp. (48 ±2%), and *Rhizobium* spp. (32±12%). Significant effect on CY was observed when seeds were treated with *Bacillus* spp. (15 ±5%), *Rhizobium* spp. (13±6%), and *Pseudomonas* spp. (8 ±3%), in decreasing order of effectiveness.

As for fungi (Fig. 4b), SE was significantly improved when seed treatments were performed with *Gliocladium* spp. (234

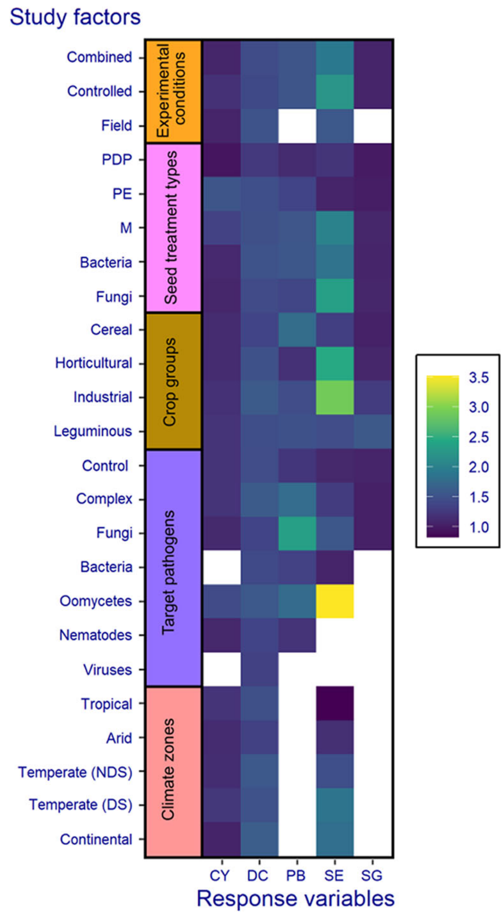

Fig. 3 Weighted average of the response ratio of the measured/studied variables for different study factors as shown by heat map graph (see Eq. 5 for detailed information). The weighted average is grouped by experimental conditions (**a**), seed treatment types (**b**), crop groups (**c**), target pathogens (**d**), and climate zones (**e**). The weighted average of the response ratio >1 in the heat map indicates a positive response while a value of <1 shows a negative response. The blank part in the heat map graph was due to no data availability. SG, seed germination; SE, seedling emergence; PB, plant biomass; DC, disease control; CY, crop yield; PDP, plant derived products; PE, plant extracts; M, microorganisms; NDS, temperate climate with no dry season; DS, temperate climate with dry season. The number of studies and observations for each response variable is reported in Table 1.

±52%), followed by *Penicillum* spp. (179±29%), *Clonostachys* spp (168±68%), and *Trichoderma* spp. (141 ±16%). All but *Clonostachys* spp. and *Gliocladium* spp. seed treatments significantly increased PB with *Penicillum* spp. being the most effective (70±34%) compared with *Trichoderma* spp. (31±11%). In contrast, seed treatments with all four fungal groups significantly enhanced DC with *Clonostachys* spp. being the most effective (69±15%) followed by *Gliocladium* spp. (59±5%), *Trichoderma* spp. (57±3%), and *Penicillum* spp. (53±13%). Finally, only seed treatments with *Trichoderma* spp. significantly enhanced CY (31±6%).

Biological seed treatments with PE provided the most significant CY increase (53±26%) followed by those with M (34 ±2%). In contrast, biological seed treatments with PDP negatively affected CY (-6%) compared with untreated seeds (Fig. 2b). Both bacterial and fungal microorganisms used for biological seed treatments significantly improved CY compared with untreated seeds (fungi +8%; $p<0.05$ vs. bacteria +10%; $p<0.05$). More details about PDP and PE treatments can be found in Table S2 and Supplementary Data 3. Only response ratio values are reported for these treatments due to a large variation between PDP and PE treatments that did not allow us to analyze these data.

Application of beneficial microorganisms to seeds allows the placement of microbial inocula into soil, thereby facilitating a rapid colonization of seedling roots and offering protection against soil-borne pests and pathogens (Papavizas 1985; Couillerot et al. 2009; O'Callaghan 2016). At the same time, replacing chemical seed treatments with biological seed treatments helps to ensure natural functioning of seed-associated bacteria, which represent an important reservoir of microorganisms playing an essential role for early plant development and vigor (Matsumoto et al. 2021). Avoiding the planting of chemically treated seeds also means enhancing seed and plant endophytes that have important functions in their host including disease suppression (Hardoim et al. 2015; Berg et al. 2016). These endophytes are negatively impacted by chemical seed treatments (Vasanthakumari et al. 2019; Chen et al. 2020).

3.4 Crop groups

SG enhancement due to biological seed treatments was significantly different among the crop groups (Figs. 2c and Fig. 3). Biological seed treatments significantly improved SG of leguminous (58±10%) and industrial crops (28±0%) while no significant improvement in SG was observed for cereal ($p= 0.05$) and horticultural ($p= 0.05$) crops (Fig. 2c). Biological seed treatments had the lowest effect on SE improvement in cereal (31±6%) while it provided the highest benefit for industrial (191±22%) and horticultural crops (145±9%). This can be explained by the fact that cereals are the most vulnerable crop groups as they are most often attacked by a myriad of seed- and soil-borne pathogens (Majumder et al. 2013) across all phases of the crop cycle.

In all crop groups, biological seed treatments significantly increased ($p<0.05$) PB compared with untreated seeds. Statistically significant differences were observed among crop groups in terms of increase in PB due to biological seed treatments with cereals drawing the most important gain (77±12%) followed by leguminous (49±8%), industrial (45±11%), and horticultural crops (18±5%). The gain in PB of cereal crops due to biological seed treatments was significantly different ($p<0.05$) compared with that of the other crop groups (Fig. 2c). In contrast, no significant difference ($p=0.05$) in PB increase due to biological seed treatments was observed between industrial and leguminous crops although both of them

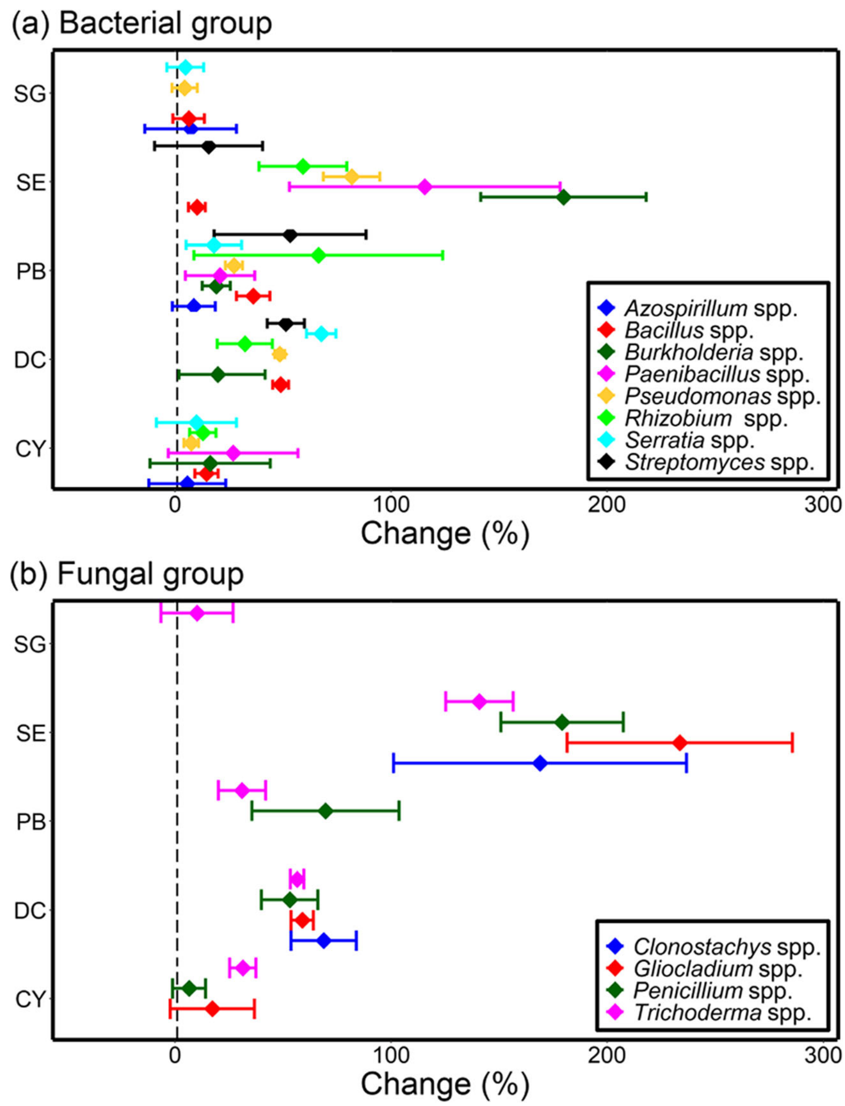

Fig. 4 Major types of microorganisms used for seed treatments. These microorganisms include groups of bacteria (**a**) and fungi (**b**) that improve crop performance and yield when applied with seed treatments. SG, seed germination; SE, seedling emergence; PB, plant biomass; DC, disease control; CY, crop yield. The number of studies and observations for each response variable is reported in Table 1.

had a significant PB gain (p<0.05) compared with that of horticultural crops.

Disease control due to biological seed treatments was observed among all crop groups with cereals benefiting the most (63±2%) followed by leguminous (54±3%), horticultural (51 ±2%), and industrial crops (42±4%). Significant differences in DC (p<0.05) in cereals crops were observed compared with leguminous, horticultural, and industrial crops. In contrast, no significant difference (p=0.05) in DC due to biological seed treatments was observed among leguminous and horticultural crops (Fig. 2c).

A significant effect of biological seed treatments on CY was observed for all crop groups with leguminous crops taking the most important advantage (20±5%), followed by industrial (18±7%), cereal (12±2%), and horticultural (12±7%) crops. There was no significant difference (p=0.05) between crop groups in terms of CY improvement due to biological seed treatments, except for the difference between cereals and legumes, with the latter taking significantly higher CY benefits than the former (p<0.05).

3.5 Biotic stresses

No significant improvement (p=0.05) on SG due to biological seed treatments was found (Fig. 2d). In contrast, biological seed treatments significantly improved SE via a better DC due to plant pathogenic oomycetes (252±11%), followed by fungi (55±8%), the pathogen complex (29±7%), and even under no pathogen inoculation conditions (9±2%). SE due to biological seed treatments was not significantly increased when diseases were caused by bacterial pathogens (7%; p=0.05). Biological seed treatments significantly increased (p<0.05) PB either under biotic stresses or under control conditions compared with untreated seeds (Fig. 2d). Biological seed treatments increased PB through significantly better control of diseases caused by plant pathogenic fungi

(133±20%), followed by the pathogen complex (78±17%), oomycetes (76±14%), bacteria (34±13%), and nematode pathogens (20±7%).

Biological seed treatments were the most effective in reducing seed and seedling diseases caused by plant pathogenic viruses (67±4%) followed by those caused by fungi (64±1%), nematodes (64±5%), bacteria (57±3%), oomycetes (43±3%), and the pathogen complex (41±3%). Significant differences ($p<0.05$) in DC were observed among diseases caused by plant pathogenic viruses, fungi, and nematodes compared with those caused by other biotic stresses or under no inoculation conditions (Fig. 2d).

Biological seed treatments improved CY through significantly better control of plant pathogenic oomycetes (43 ±17%), the pathogen complex (21±7%), and pathogenic fungi (11±4%). In contrast, no significant yield gain response (p=0.05) due to biological seed treatments was observed due to better control of plant pathogenic nematodes (Fig. 2d). Likewise, no significant CY increase due to biological seed treatments (p=0.05) was observed between the pathogen complex and control conditions or between stress due to pathogenic fungi and nematodes. No CY data were available for stress caused by plant pathogenic bacteria and viruses (Fig. 3).

3.6 Climate zones

Biological seed treatments significantly enhanced ($p<0.05$) SE across all but tropical climate zones. The magnitude of SE increment was significantly higher in temperate DS (86 ±35.16%), followed by continental (80±12%), and temperate NDS (47±10%) climate zones, compared with the arid zone (17±11%) (Fig. 2e). Among the response variables, SE due to biological seed treatments had the most important gain compared with DC and CY (Fig. 3). Significant negative reduction in SE due to biological seed treatments was observed under tropical climate (18±16%). DC under field conditions due to biological seed treatments was significantly increased in arid (67±3%), followed by tropical (52±5%), temperate DS (50 ±6%), temperate NDS (43±4%), and continental (37±5%) climate zones (Figs. 2e and 3).

Biological seed treatments significantly increased CY gain that was the highest under temperate DS (23±11%) followed by tropical (21±9%), temperate NDS (14±5%), arid (12±5%), and continental (6±5%) climate zones. There was no significant difference (p=0.05) between climate zones in terms of CY improvement due to biological seed treatments, except for the difference between continental climate zone and temperate DS or tropical climate zones.

We found a significant effect of climate on the effectiveness of biological seed treatments in improving crop development and yield due to enhanced disease control. For instance, SE was negatively affected by biological seed treatments under tropical climate zones compared with others, which could be due to the effect of soil moisture, elevated temperature, or their interactions. Indeed, regions with a lower frequency of rainfall are more likely to benefit from the planting of biologically treated seeds, as observed for seed priming (Carrillo-Reche et al. 2018).

The planting of biologically treated seeds significantly increased CY gain across all climate zones compared with the untreated seeds. However, the extent of benefit provided by this practice was different among the climate zones with all but continental climate zones benefitting the least. Our results corroborate the conclusion of a recent meta-analysis where on-farm seed priming had the largest positive response on CY under arid or semi-arid climates (Carrillo-Reche et al. 2018). We found that biological seed treatments did not improve SE in tropical regions but enhanced DC in the same regions. This implies that CY improvement in this region was mainly due to an increased DC after SE. However, in other climate zones, improved CY was related both to enhanced SE and increased DC due to the planting of biologically treated seeds.

4 Conclusion

Information on the potential of different biological seed treatments across different crop groups or climatic zones, in terms of crop performance, is particularly useful for stakeholders of the agri-food system for decision making. Based on our results, the planting of biologically treated seeds should be encouraged across climate zones or crop groups where this practice already ensures increased crop performance. In contrast, further improvements of the currently used biological seed treatment methods, and the development of new ones, should be considered for areas or crop groups that provide lower yield gain.

The planting of biologically treated seeds with microorganisms can also mitigate the impact of climate change due to improved tolerance to abiotic stresses such as heat stress (Abd El-Daim et al. 2014; O'Callaghan 2016). Indeed, no inoculation conditions considered in this meta-analysis were related to treatments without artificial inoculation of plant pathogens although other abiotic stresses were naturally occurring under these conditions. Significant improvement in SE and CY under non-inoculated conditions observed in this meta-analysis is a clear indication that biological seed treatments have potential to increase crop performance and yield under climate change.

Finally, our meta-analysis showed that biological seed treatments have potential to ensure long-term sustainability of the agri-food system with no or reduced human health and environmental impacts. Our results therefore are of great significance for the stakeholders who are looking to foster the sustainability of the agri-food system.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-022-00761-z.

Acknowledgements This study was supported by the FAST project (Faisabilité et Evaluation de Systèmes de Cultures Economes en pesticides en l'Absence répétée de Semences Traitées) funded by the French Agency for Biodiversity, by credits from the royalty for diffuse pollution, attributed to the funding of the Ecophyto plan. We thank Prof. Stephen N. Wegulo, the University of Nebraska-Lincoln, USA, for proofreading of this paper, and the Managing Editor for her useful comments which helped improve this paper.

Code availability Not applicable.

Authors' contributions Conceptualization: JRL; Methodology: ES, JRL, DCC; Investigation: ES, JRL; Visualization: JRL, ES, DCC; Writing original draft: JRL; Writing, review & editing: ES, JRL.

Funding The study was supported by the FAST project (please see the acknowledgement section for detailed information).

Data availability All the data used to write this bibliographic review come from the publications listed in the supplementary materials.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Abd El-Daim IA, Bejai S, Meijer J (2014) Improved heat stress tolerance of wheat seedlings by bacterial seed treatment. Plant Soil 379:337–350. https://doi.org/10.1007/s11104-014-2063-3

AGRICAN (2020) Enquête agriculture & cancer. p 60. www.agrican.fr

Aktar MW, Sengupta D, Chowdhury A (2009) Impact of pesticides use in agriculture: their benefits and hazards. Interdiscip Toxicol 2:1–12. https://doi.org/10.2478/v10102-009-0001-7

Berg G, Rybakova D, Grube M, Köberl M (2016) The plant microbiome explored: implications for experimental botany. J Exp Bot 67:995–1002. https://doi.org/10.1093/jxb/erv466

Carrillo-Reche J, Vallejo-Marín M, Quilliam RS (2018) Quantifying the potential of 'on-farm' seed priming to increase crop performance in developing countries. A meta-analysis. Agron Sustain Dev 38:64. https://doi.org/10.1007/s13593-018-0536-0

Chen X, Krug L, Yang M et al (2020) Conventional seed coating reduces prevalence of proteobacterial endophytes in Nicotiana tabacum. Ind Crops Prod 155:112784. https://doi.org/10.1016/j.indcrop.2020.112784

Cooper J, Dobson H (2007) The benefits of pesticides to mankind and the environment. Crop Prot. 26:1337–1348

Couillerot O, Prigent-Combaret C, Caballero-Mellado J, Moënne-Loccoz Y (2009) Pseudomonas fluorescens and closely-related fluorescent pseudomonads as biocontrol agents of soil-borne phytopathogens. Lett Appl Microbiol 48:505–512. https://doi.org/10.1111/j.1472-765X.2009.02566.x

Fadel Sartori F, Floriano Pimpinato R, Tornisielo VL et al (2020) Soybean seed treatment: how do fungicides translocate in plants? Pest Manag Sci. https://doi.org/10.1002/ps.5771

Fernández-Vizcaíno E, Ortiz-Santaliestra ME, Fernández-Tizón M et al (2021) Bird exposure to fungicides through the consumption of treated seeds: a study of wild red-legged partridges in central Spain. Environ Pollut:118335. https://doi.org/10.1016/j.envpol.2021.118335

Foster K, You MP, Nietschke B et al (2017) Widespread decline of subterranean clover pastures across diverse climatic zones is driven by soilborne root disease pathogen complexes. Crop Pasture Sci 68:33–44. https://doi.org/10.1071/CP16098

Gomes YCB, Dalchiavon FC, de Assis Valadão FC (2017) Joint use of fungicides, insecticides and inoculants in the treatment of soybean seeds. Rev Ceres, Viçosa 64:258–265. https://doi.org/10.1590/0034-737x201764030006

Gurevitch J, Hedges LV (1999) Statistical issues in ecological meta-analyses. Ecology 80:1142–1149. https://doi.org/10.1890/0012-9658(1999)080[1142:SIIEMA]2.0.CO;2

Han R, Wu Z, Huang Z et al (2021) Tracking pesticide exposure to operating workers for risk assessment in seed coating with tebuconazole and carbofuran. Pest Manag Sci n/a. https://doi.org/10.1002/ps.6315

Hardoim PR, van Overbeek LS, Berg G et al (2015) The hidden world within plants: ecological and evolutionary considerations for defining functioning of microbial endophytes. Microbiol Mol Biol Rev 79:293 LP – 320. https://doi.org/10.1128/MMBR.00050-14

Hedges LV, Gurevitch J, Curtis PS (1999) The meta-analysis of response ratios in experimental ecology. Ecology 80:1150–1156. https://doi.org/10.2307/177062

Hitaj C, Smith DJ, Code A et al (2020) Sowing uncertainty: what we do and don't know about the planting of pesticide-treated seed. Bioscience 70:390–403. https://doi.org/10.1093/biosci/biaa019

Knapp S, van der Heijden MGA (2018) A global meta-analysis of yield stability in organic and conservation agriculture. Nat Commun 9:3632. https://doi.org/10.1038/s41467-018-05956-1

Lamichhane JR (2020) Parsimonius use of pesticide-treated seeds: an integrated pest management framework. Trends Plant Sci 25:1070–1073. https://doi.org/10.1016/j.tplants.2020.08.002

Lamichhane JR, Debaeke P, Steinberg C et al (2018) Abiotic and biotic factors affecting crop seed germination and seedling emergence: a conceptual framework. Plant Soil 432:1–28. https://doi.org/10.1007/s11104-018-3780-9

Lamichhane JR, Venturi V (2015) Synergisms between microbial pathogens in plant disease complexes: a growing trend. Front Plant Sci 6. https://doi.org/10.3389/fpls.2015.00385

Lamichhane JR, You MP, Barbetti MJ, Aubertot J-N (2020a) Crop establishment simulator: a qualitative aggregative model to predict the role of phytobiomes on field crop establishment. Phytobiomes J 4:327–339. https://doi.org/10.1094/PBIOMES-05-20-0036-R

Lamichhane JR, You MP, Laudinot V et al (2020b) Revisiting sustainability of fungicide seed treatments for field crops. Plant Dis 104:610–623. https://doi.org/10.1094/PDIS-06-19-1157-FE

Li C, Hoffland E, Kuyper TW et al (2020a) Syndromes of production in intercropping impact yield gains. Nat Plants 6:653–660. https://doi.org/10.1038/s41477-020-0680-9

Li Y, Miao R, Khanna M (2020b) Neonicotinoids and decline in bird biodiversity in the United States. Nat Sustain 3:1027–1035. https://doi.org/10.1038/s41893-020-0582-x

Li Y, Song D, Liang S et al (2020c) Effect of no-tillage on soil bacterial and fungal community diversity: a meta-analysis. Soil Tillage Res 204:104721. https://doi.org/10.1016/j.still.2020.104721

Lundin O, Malsher G, Högfeldt C, Bommarco R (2020) Pest management and yield in spring oilseed rape without neonicotinoid seed treatments. Crop Prot 137:105261. https://doi.org/10.1016/j.cropro.2020.105261

Main AR, Webb EB, Goyne KW, Mengel D (2020) Reduced species richness of native bees in field margins associated with neonicotinoid concentrations in non-target soils. Agric Ecosyst Environ 287:106693. https://doi.org/10.1016/j.agee.2019.106693

Majumder D, Rajesh T, Suting EG, Debbarma A (2013) Detection of seed borne pathogens in wheat: recent trends. Aust J Crop Sci 7: 500–507

Marty C, BassiriRad H (2014) Seed germination and rising atmospheric CO2 concentration: a meta-analysis of parental and direct effects. New Phytol 202:401–414. https://doi.org/10.1111/nph.12691

Matsumoto H, Fan X, Wang Y et al (2021) Bacterial seed endophyte shapes disease resistance in rice. Nat Plants 7:60–72. https://doi.org/10.1038/s41477-020-00826-5

Mourtzinis S, Krupke CH, Esker PD et al (2019) Neonicotinoid seed treatments of soybean provide negligible benefits to US farmers. Sci Rep 9:11207. https://doi.org/10.1038/s41598-019-47442-8

Munkvold GP, Watrin C, Scheller M et al (2014) Benefits of chemical seed treatments on crop yield and quality. In: Gullino ML, Munkvold G (eds) Global Perspectives on the Health of Seeds and Plant Propagation Material. Springer Netherlands, Dordrecht, pp 89–103

Nettles R, Watkins J, Ricks K et al (2016) Influence of pesticide seed treatments on rhizosphere fungal and bacterial communities and leaf fungal endophyte communities in maize and soybean. Appl Soil Ecol 102:61–69. https://doi.org/10.1016/j.apsoil.2016.02.008

Neyeloff JL, Fuchs SC, Moreira LB (2012) Meta-analyses and Forest plots using a microsoft excel spreadsheet: step-by-step guide focusing on descriptive data analysis. BMC Res Notes 5:52. https://doi.org/10.1186/1756-0500-5-52

O'Callaghan M (2016) Microbial inoculation of seed for improved crop performance: issues and opportunities. Appl Microbiol Biotechnol 100:5729–5746. https://doi.org/10.1007/s00253-016-7590-9

Oerke EC (2006) Crop losses to pests. J Agric Sci 144:31–43. https://doi.org/10.1017/S0021859605005708

Papavizas GC (1985) Trichoderma and gliocladium: biology, ecology, and potential for biocontrol. Annu Rev Phytopathol 23:23–54. https://doi.org/10.1146/annurev.py.23.090185.000323

Rojas JA, Jacobs JL, Napieralski S et al (2016) Oomycete species associated with soybean seedlings in North America—Part II: diversity and ecology in relation to environmental and edaphic factors. Phytopathology 107:293–304. https://doi.org/10.1094/PHYTO-04-16-0176-R

Rosenberg MS, Garrett KA, Su Z, Bowden RL (2004) Meta-analysis in plant pathology: synthesizing research results. Phytopathology® 94: 1013–1017. https://doi.org/10.1094/PHYTO.2004.94.9.1013

Rossman DR, Byrne AM, Chilvers MI (2018) Profitability and efficacy of soybean seed treatment in Michigan. Crop Prot 114:44–52. https://doi.org/10.1016/j.cropro.2018.08.003

Rundlof M, Andersson GKS, Bommarco R et al (2015) Seed coating with a neonicotinoid insecticide negatively affects wild bees. Nature 521: 77–80. https://doi.org/10.1038/nature14420

Sappington TW, Hesler LS, Allen KC et al (2018) Prevalence of sporadic insect pests of seedling corn and factors affecting risk of infestation. J Integr Pest Manag 9. https://doi.org/10.1093/jipm/pmx020

Savary S, Willocquet L, Pethybridge SJ et al (2019) The global burden of pathogens and pests on major food crops. Nat Ecol Evol 3:430–439. https://doi.org/10.1038/s41559-018-0793-y

Serrano M, Robertson AE (2018) The effect of cold stress on damping-off of soybean caused by Pythium sylvaticum. Plant Dis 102:2194–2200. https://doi.org/10.1094/PDIS-12-17-1963-RE

Simpson RJ, Richardson AE, Riley IT et al (2011) Damage to roots of Trifolium subterraneum L. (subterranean clover), failure of seedlings to establish and the presence of root pathogens during autumn-winter. Grass Forage Sci. https://doi.org/10.1111/j.1365-2494.2011.00822.x

Soltani E, Baskin CC, Baskin JM et al (2018) A meta-analysis of the effects of frugivory (endozoochory) on seed germination: role of seed size and kind of dormancy. Plant Ecol 219:1283–1294. https://doi.org/10.1007/s11258-018-0878-3

Soltani E, Soltani A (2015) Meta-analysis of seed priming effects on seed germination, seedling emergence and crop yield: Iranian studies. Int J Plant Prod 9:413–432

Traveset A, Verdu M (2002) A meta-analysis of the effect of gut treatment on seed germination. In: Levey DJ, Silva WR, Galetti M (eds) Seed dispersal and frugivory: ecology, evolution and conservation. CABI International, Wallingford, UK, pp 339–350

van Agtmaal M, Straathof A, Termorshuizen A et al (2017) Exploring the reservoir of potential fungal plant pathogens in agricultural soil. Appl Soil Ecol 121:152–160. https://doi.org/10.1016/j.apsoil.2017.09.032

Vasanthakumari MM, Shridhar J, Madhura RJ et al (2019) Role of endophytes in early seedling growth of plants: a test using systemic fungicide seed treatment. Plant Physiol Reports 24:86–95. https://doi.org/10.1007/s40502-018-0404-6

White KE, Hoppin JA (2004) Seed treatment and its implication for fungicide exposure assessment. J Expo Anal Environ Epidemiol 14:195–203. https://doi.org/10.1038/sj.jea.7500312

Wrather A, Shannon G, Balardin R et al (2010) Effect of diseases on soybean yield in the top eight producing countries in 2006. Plant Heal Prog 11:29. https://doi.org/10.1094/PHP-2010-0102-01-RS

You MP, Lamichhane JR, Aubertot J-N, Barbetti MJ (2020) Understanding why effective fungicides against individual soilborne pathogens are ineffective with soilborne pathogen complexes. Plant Dis 104:904–920. https://doi.org/10.1094/pdis-06-19-1252-re

Zaller JG, König N, Tiefenbacher A et al (2016) Pesticide seed dressings can affect the activity of various soil organisms and reduce decomposition of plant material. BMC Ecol 16:37. https://doi.org/10.1186/s12898-016-0092-x

References of the meta-analysis

Abeysinghe S (2009) Use of nonpathogenic *Fusarium oxysporum* and rhizobacteria for suppression of Fusarium root and stem rot of *Cucumis sativus* caused by *Fusarium oxysporum* f. sp. *radicis-cucumerinum*. Arch. Phytopathol Plant Prot 42:73–82. https://doi.org/10.1080/03235400600940947

Adandonon A, Aveling TAS, Labuschagne N, Tamo M (2006) Biocontrol agents in combination with *Moringa oleifera* extract for integrated control of Sclerotium-caused cowpea damping-off and stem rot. Eur J Plant pathol 115:409–418. https://doi.org/10.1007/s10658-006-9031-6

Adekunle AT, Cardwell KF, Florini DA, Ikotun T (2001) Seed treatment with Trichoderma species for control of damping-off of cowpea caused by *Macrophomina phaseolina*. Biocontrol Sci Technol 11: 449–457. https://doi.org/10.1080/09583150120067481

Adekunle AT, Ikotun T, Florini DA, Cardwell KF (2006) Field evaluation of selected formulations of Trichoderma species as seed treatment to control damping-off of cowpea caused by *Macrophomina phaseolina*. Afr J Biotechnol 5:419–424

Adetuyi FC (1989) *In vitro* inhibition of some fungal pathogens by bacterial isolates from rice seed coat. J Plant Dis Prot 96:486–493

Afsharmanesh H, Ahmadzadeh M, Javan-Nikkhah M, Behboudi K (2010) Characterization of the antagonistic activity of a new indigenous strain of *Pseudomonas fluorescens* isolated from onion rhizosphere. J Plant Pathol 92:187–194. https://doi.org/10.4454/jpp.v92i1.29

Afzal A, Bano A, Fatima M (2010) Higher soybean yield by inoculation with N-fixing and P-solubilizing bacteria. Agron Sustain Dev 30: 487–495. https://doi.org/10.1051/agro/2009041

Agaras BC, Noguera F, Anta GG et al (2020) Biocontrol potential index of pseudomonads, instead of their direct-growth promotion traits, is a predictor of seed inoculation effect on crop productivity under field conditions. Biol Con 143:104209. https://doi.org/10.1016/j.biocontrol.2020.104209

Ahmed AS, Ezziyyani M, Sánchez CP, Candela ME (2003) Effect of chitin on biological control activity of *Bacillus* spp. and *Trichoderma harzianum* against root rot disease in pepper (*Capsicum annuum*) plants. Eur J Plant Pathol 109:633–637. https://doi.org/10.1023/A:1024734216814

Ahmed S (2017) Seed bacterization with Pseudomonas isolates against wheat cyst nematode (*Heterodera avenae*). Bangladesh J. Bot 46: 995–1000

Aiyaz M, Divakara ST, Nayaka SC et al (2015) Application of beneficial rhizospheric microbes for the mitigation of seed-borne mycotoxigenic fungal infection and mycotoxins in maize. Biocon Sci Technol 25:1105–1119. https://doi.org/10.1080/09583157.2015.1020760

Akhter W, Bhuiyan MKA, Sultana F, Hossain MM (2015) Integrated effect of microbial antagonist, organic amendment and fungicide in controlling seedling mortality (*Rhizoctonia solani*) and improving yield in pea (*Pisum sativum* L.). C R Biol 338:21–28. https://doi.org/10.1016/j.crvi.2014.10.003

Al-Daghari DSS, Al-Sadi AM, Janke R et al (2020) Potential of indigenous antagonistic rhizobacteria in the biological control of Monosporascus root rot and vine decline disease of muskmelon. Acta Agric Scand B Soil Plant Sci 70:371–380. https://doi.org/10.1080/09064710.2020.1748703

Ali B (2015) Bacterial auxin signaling: comparative study of growth induction in *Arabidopsis thaliana* and *Triticum aestivum*. Turk J Bot 39:1–9

Ali B, Sabri AN, Hasnain S (2010) Rhizobacterial potential to alter auxin content and growth of *Vigna radiata* (L.). World J. Microbiol. Biotechnol 26:1379–1384. https://doi.org/10.1007/s11274-010-0310-1

Al-Mughrabi KI (2010) Biological control of Fusarium dry rot and other potato tuber diseases using *Pseudomonas fluorescens* and *Enterobacter cloacae*. Biol Control 53:280–284. https://doi.org/10.1016/j.biocontrol.2010.01.010

Al-Mughrabi KI, Vikram A, Poirier R et al (2016) Management of common scab of potato in the field using biopesticides, fungicides, soil additives, or soil fumigants. Biocontrol Sci Technol 26:125–135. https://doi.org/10.1080/09583157.2015.1079809

Alsahli A, Alaraidh I, Rashad Y, Razil EA (2018) Extract from *Curcuma longa* L. triggers the sunflower immune system and induces defence-related genes against Fusarium root rot. Phytopathol Mediterr 57:26–36. https://doi.org/10.14601/Phytopathol_Mediterr-21176

Alström S (1991) Induction of disease resistance in common bean susceptible to halo blight bacterial pathogen after seed bacterization with rhizosphere pseudomonads. J Gen Appl Microbiol 37:495–501

Amein T, Wright SA, Wikström M et al (2011) Evaluation of non-chemical seed treatment methods for control of *Alternaria brassicicola* on cabbage seeds. J Plant Dis Prot 118:214–221. https://doi.org/10.1007/BF03356406

Andresen M, Wulff EG, Mbega ER et al (2015) Seed treatment with an aqueous extract of *Agave sisalana* improves seed health and seedling growth of sorghum. Eur J Plant Pathol 141:119–132. https://doi.org/10.1007/s10658-014-0530-6

Anis M, Abbasi MW, Zaki MJ (2010) Bioefficacy of microbial antagonists against *Macrophomina phaseolina* on sunflower. Pak J Bot 42:2935–2929

Anith KN (2009) Mature coconut as a bio-fermentor for multiplication of plant growth promoting rhizobacteria. Curr Sci 97:1647–1653

Antonelli M, Reda R, Aleandri MP et al (2013) Plant growth-promoting bacteria from solarized soil with the ability to protect melon against root rot and vine decline caused by *Monosporascus cannonballus*. J Phytopathol 161:485–496. https://doi.org/10.1111/jph.12095

Arkhipova T, Galimsyanova N, Kuzmina L et al (2019) Effect of seed bacterization with plant growth-promoting bacteria on wheat productivity and phosphorus mobility in the rhizosphere. Plant, Soil Environ 65:313–319. https://doi.org/10.17221/752/2018-PSE

Atkinson TG, Neal JL Jr, Larson RI (1974) Root rot reaction in wheat: resistance not mediated by rhizosphere or laimosphere antagonists. Phytopathology 64:97–101

Atri A, Oberoi H, Kumar P (2019) Rhizosphere Trichoderma isolates as potential biocontrol agent for maydis leaf blight pathogen (*Bipolaris maydis*) in fodder maize. Proc Indian National Sci Acad 85:885–893

Babaeipoor E, Mirzaei S, Danesh YR et al (2011) Evaluation of some antagonistic bacteria in biological control of *Gaeumannomyces graminis* var *tritici* causal agent of wheat take-all disease in Iran. Afr J Microbiol Res 5:5165–5173

Bakaeva M, Kuzina E, Vysotskaya L et al (2020) Capacity of Pseudomonas strains to degrade hydrocarbons, produce auxins and maintain plant growth under normal conditions and in the presence of petroleum contaminants. Plants 9:379. https://doi.org/10.3390/plants9030379

Bakhshi E, Safaie N, Shamsbakhsh M (2018) *Bacillus amyloliquefaciens* as a biocontrol agent improves the management of charcoal root rot in melon. J Agric Sci Technol 20:597–607 URL: http://jast.modares.ac.ir/article-23-20348-en.html

Bankole SA, Adebanjo A (1996) Biocontrol of brown blotch of cowpea caused by *Colletotrichum truncatum* with *Trichoderma viride*. Crop Prot 15:633–636

Banyal DK, Sood VK, Singh A, Mawar R (2016) Integrated management of oat diseases in north-western Himalaya. Range Manag Agrofor 37:84–87

Bardin SD, Huang HC, Moyer JR (2004) Control of Pythium damping-off of sugar beet by seed treatment with crop straw powders and a biocontrol agent. Biol Control 29:453–460. https://doi.org/10.1016/j.biocontrol.2003.09.001

Bardin SD, Huang HC, Liu L, Yanke LJ (2003) Control, by microbial seed treatment, of damping-off caused by *Pythium* sp. on canola, safflower, dry pea, and sugar beet. Can J Plant Pathol 25:268–275. https://doi.org/10.1080/07060660309507079

Basha H, Ramanujam B (2015) Growth promotion effect of *Pichia guilliermondii* in chilli and biocontrol potential of *Hanseniaspora uvarum* against *Colletotrichum capsici* causing fruit rot. Biocontrol Sci Technol 25:185–206. https://doi.org/10.1080/09583157.2014.968092

Bashan Y, de-Bashan LE (2002) Reduction of bacterial speck (*Pseudomonas syringae* pv. *tomato*) of tomato by combined treatments of plant growth-promoting bacterium, *Azospirillum brasilense*, streptomycin sulfate, and chemo-thermal seed treatment.

Eur J Plant Pathol 108:821–829. https://doi.org/10.1023/A:1021274419518

Belimov AA, Kunakova AM, Safronova VI et al (2004) Employment of rhizobacteria for the inoculation of barley plants cultivated in soil contaminated with lead and cadmium. Microbiology 73:99–106

Bernabeu PR, Garcia SS, López AC et al (2018) Assessment of bacterial inoculant formulated with *Paraburkholderia tropica* to enhance wheat productivity. World J Microbiol Biotechnol 34:1–10

Bevivino A, Dalmastri C, Tabacchioni S, Chiarini L (2000) Efficacy of *Burkholderia cepacia* MCI 7 in disease suppression and growth promotion of maize. Biol Fertil Soils 31:225–231. https://doi.org/10.1007/s003740050649

Bevivino A, Sarrocco S, Dalmastri C et al (1998) Characterization of a free-living maize-rhizosphere population of *Burkholderia cepacia*: effect of seed treatment on disease suppression and growth promotion of maize. FEMS Microbiol Ecol 27:225–237. https://doi.org/10.1111/j.1574-6941.1998.tb00539.x

Bhattacharjya S, Chandra R (2013) Effect of inoculation methods of *Mesorhizobium ciceri* and PGPR in chickpea (*Cicer areietinum* L.) on symbiotic traits, yields, nutrient uptake and soil properties. Legume Res 36:331–337

Birch ANE, Robertson WM, Geoghegan IE et al (1993) DMDP-a plant-derived sugar analogue with systemic activity against plant parasitic nematodes. Nematologica 39:521–535. https://doi.org/10.1163/187529293X00466

Bisht SC, Mishra PK (2013) Ascending migration of endophytic *Bacillus thuringiensis* and assessment of benefits to different legumes of NW Himalayas. Eur J Soil Biol 56:56–64. https://doi.org/10.1016/j.ejsobi.2013.02.004

Bora T, Özaktan H, Göre E, Aslan EMEK (2004) Biological control of *Fusarium oxysporum* f. sp. *melonis* by wettable powder formulations of the two strains of *Pseudomonas putida*. J Phytopathol 152:471–475. https://doi.org/10.1111/j.1439-0434.2004.00877.x

Borgi MA, Saidi I, Moula A et al (2020) The attractive *Serratia plymuthica* BMA1 strain with high rock phosphate-solubilizing activity and its effect on the growth and phosphorus uptake by *Vicia faba* L. plants. Geomicrobiol J 37:437–445. https://doi.org/10.1080/01490451.2020.1716892

Boruah HD, Kumar BD (2002) Plant disease suppression and growth promotion by a fluorescent Pseudomonas strain. Folia Microbiol 47:137–143. https://doi.org/10.1007/BF02817671

Boruah HD, Rabha BK, Saikia N, Kumar BD (2003) Fluorescent Pseudomonas influences palisade mesophyll development and spatial root development in *Phaseolus vulgaris*. Plant Soil 256:291–301

Boudyach EH, Fatmi M, Boubaker H et al (2004) Effectiveness of fluorescent pseudomonads strains HF 22 and HF 142 to control bacterial canker of tomato. JFAE 2:115–120

Boukaya N, Goudjal Y, Zamoum M et al (2018) Biocontrol and plant-growth-promoting capacities of actinobacterial strains from the Algerian Sahara and characterisation of *Streptosporangium becharense* SG1 as a promising biocontrol agent. Biocontrol Sci Technol 28:858–873. https://doi.org/10.1080/09583157.2018.1501466

Bowers JH, Parke JL (1993) Epidemiology of Pythium damping-off and Aphanomyces root rot of peas after seed treatment with bacterial agents for biological control. Phytopathology 83:1466–1473

Breedt G, Labuschagne N, Coutinho TA (2017) Seed treatment with selected plant growth-promoting rhizobacteria increases maize yield in the field. Ann Appl Biol 171:229–236. https://doi.org/10.1111/aab.12366

Burgess DR, Keane PJ (1997) Biological control of Botrytis cinerea on chickpea seed with *Trichoderma* spp. and *Gliocladium roseum*: indigenous versus non-indigenous isolates. Plant Pathol 46:910–918. https://doi.org/10.1046/j.1365-3059.1997.d01-77.x

Burgess DR, Bretag T, Keane PJ (1997) Biocontrol of seedborne *Botrytis cinerea* in chickpea with *Gliocladium roseum*. Plant Pathol 46:298–305. https://doi.org/10.1046/j.1365-3059.1997.d01-17.x

Burr TJ, Schroth MN, Suslow T (1978) Increased potato yields by treatment of seed pieces with specific strains of *Pseudomonas fluorescens* and *P. putida*. Phytopathology 68:1377–1383

Callan NW, Mathre D, Miller JB (1990) Bio-priming seed treatment for biological control of *Pythium ultimum* preemergence damping-off in sh-2 sweet corn. Plant Dis 74:368–372

Callan NW, Mathre DE, Miller JB (1991) Field performance of sweet corn seed bio-primed and coated with *Pseudomonas fluorescens* AB254. HortScience 26:1163–1165

Carvalho DD, Lobo Junior M, Martins I et al (2014) Biological control of *Fusarium oxysporum* f. sp. *phaseoli* by *Trichoderma harzianum* and its use for common bean seed treatment. Trop Plant Pathol 39:384–391. https://doi.org/10.1590/S1982-56762014000500005

Carvalho DDC, de Mello SCM, Martins I, Lobo M (2015) Biological control of Fusarium wilt on common beans by in-furrow application of *Trichoderma harzianum*. Trop Plant Pathol 40:375–381. https://doi.org/10.1007/s40858-015-0057-1

Carvalho DDC, Mello SCMD, Lobo Júnior M, Geraldine AM (2011) Biocontrol of seed pathogens and growth promotion of common bean seedlings by *Trichoderma harzianum*. Pesqui Agropecu Bras 46:822–828. https://doi.org/10.1590/S0100-204X2011000800006

Cattanêo AJ, Stangarlin JR, Bassegio D, Santos RF (2016) Crambe affected by biological and chemical seed treatments. Bragantia 75:292–298. https://doi.org/10.1590/1678-4499.565

Chandel S, Kumar V (2018) Effect of plant extracts as pre-storage seed treatment on storage fungi, germination percentage and seedling vigour of pea (*Pisum sativum*). Indian J Agric Sci 8:1476–1481

Chandra NS, Udaya Shankar AC, Reddy MS et al (2009) Control of *Fusarium verticillioides*, cause of ear rot of maize, by *Pseudomonas fluorescens*. Pest Manag Sci 65:769–775. https://doi.org/10.1002/ps.1751

Chandra S, Choure K, Dubey RC, Maheshwari DK (2007) Rhizosphere competent Mesorhizobiumloti MP6 induces root hair curling, inhibits *Sclerotinia sclerotiorum* and enhances growth of Indian mustard (*Brassica campestris*). Braz J Microbiol 38:124–130. https://doi.org/10.1590/S1517-83822007000100026

Chandrashekhara NRS, Manjunath G, Deepak S, Shekar SH (2010) Seed treatment with aqueous extract of *Viscum album* induces resistance to pearl millet downy mildew pathogen. J Plant Interact 5:283–291. https://doi.org/10.1080/17429140903556539

Cheema HK, Sharma P, Singh R et al (2009) Efficacy and compatibility of insecticides, fungicide and Rhizobium inoculant in combination for seed treatment in chickpea (*Cicer arietinum*). Indian J Agric Sci 79:90

Chemeltorit PP, Mutaqin KH, Widodo W (2017) Combining *Trichoderma hamatum* THSW13 and *Pseudomonas aeruginosa* BJ10–86: a synergistic chili pepper seed treatment for *Phytophthora capsici* infested soil. Eur J Plant Pathol 147:157–166. https://doi.org/10.1007/s10658-016-0988-5

Cheng X, Ji X, Ge Y et al (2019) Characterization of antagonistic *Bacillus methylotrophicus* isolated from rhizosphere and its biocontrol effects on maize stalk rot. Phytopathology 109:571–581. https://doi.org/10.1094/PHYTO-07-18-0220-R

Chithrashree UAC, Nayaka SC, Reddy MS, Srinivas C (2011) Plant growth-promoting rhizobacteria mediate induced systemic resistance in rice against bacterial leaf blight caused by *Xanthomonas oryzae* pv. *oryzae*. Biol Control 59:114–122. https://doi.org/10.1016/j.biocontrol.2011.06.010

Chiuraise N, Yobo KS, Laing MD (2015) Seed treatment with *Trichoderma harzianum* strain kd formulation reduced aflatoxin contamination in groundnuts. J Plant Dis Protec 122:74–80. https://doi.org/10.1007/BF03356534

Christian EJ, Goggi AS (2008) Aromatic plant oils as fungicide for organic corn production. Crop Sci 48:1941–1951. https://doi.org/10.2135/cropsci2007.06.0341

Colla G, Rouphael Y, Bonini P, Cardarelli M (2015) Coating seeds with endophytic fungi enhances growth, nutrient uptake, yield and grain quality of winter wheat. Int J Plant Prod 9:171–190. https://doi.org/10.22069/ijpp.2015.2042

Correa OS, Montecchia MS, Berti MF et al (2009) *Bacillus amyloliquefaciens* BNM122, a potential microbial biocontrol agent applied on soybean seeds, causes a minor impact on rhizosphere and soil microbial communities. Appl Soil Ecol 41:185–194. https://doi.org/10.1016/j.apsoil.2008.10.007

Coşkuntuna A, Özer N (2008) Biological control of onion basal rot disease using *Trichoderma harzianum* and induction of antifungal compounds in onion set following seed treatment. Crop Prot 27:330–336. https://doi.org/10.1016/j.cropro.2007.06.002

Cubeta MA, Echandi E (1991) Biological control of *Rhizoctonia* and *Pythium* damping-off of cucumber: an integrated approach. Biol Control 1:227–236

Custódio CC, de Araújo FF, Ribeiro AM, de Souza Filho NV, Machado-Neto NB (2013) Seed treatment with *Bacillus subtilis* or indol butyric acid: germination and early development of bean seedlings. Interciencia 38:273–279

da Silva AC, Souza PED, Machado JDC, Silva BMD, Pinto JEBP (2012) Effectiveness of essential oils in the treatment of *Colletotrichum truncatum*-infected soybean seeds. Tropic Plant Pathol 37:305–313. https://doi.org/10.1590/S1982-56762012000500001

Dahiya A, Sharma R, Sindhu S, Sindhu SS (2019) Resource partitioning in the rhizosphere by inoculated Bacillus spp. towards growth stimulation of wheat and suppression of wild oat (*Avena fatua* L.) weed. Physiol Mol Biol Plants 25:1483–1495. https://doi.org/10.1007/s12298-019-00710-3

Dalzotto L, Tortelli B, Stefanski FS et al (2020) Creole bean seeds microbiolization with doses of *Trichoderma harzianum*. Ciênc Rural 50:e20190542. https://doi.org/10.1590/0103-8478cr20190542

Dandurand LM, Knudsen GR (1993) Influence of Pseudomonas fluorescens on hyphal growth and biocontrol activity of *Trichoderma harzianum* in the spermosphere and rhizosphere of pea. Phytopathology 83:265–270

Das IK, Indira S, Annapurna A, Seetharama N (2008) Biocontrol of charcoal rot in sorghum by fluorescent pseudomonads associated with the rhizosphere. Crop Prot 27:1407–1414. https://doi.org/10.1016/j.cropro.2008.07.001

DasGupta SM, Khan N, Nautiyal CS (2006) Biologic control ability of plant growth–promoting *Paenibacillus lentimorbus* NRRL B-30488 isolated from milk. Curr Microbiol 53:502–505. https://doi.org/10.1007/s00284-006-0261-9

de Araujo FF (2008) Inoculação de sementes com *Bacillus subtilis*, formulado com farinha de ostras e desenvolvimento de milho, soja e algodão. Ciênc Agrotec 32:456–462 (in Portuguese). https://doi.org/10.1590/S1413-70542008000200017

de Jensen CE, Percich JA, Graham PH (2002) Integrated management strategies of bean root rot with *Bacillus subtilis* and *Rhizobium* in Minnesota. Field Crops Res 74:107–115. https://doi.org/10.1016/S0378-4290(01)00200-3

De Lima CB, Rentschler LLA, Bueno JT, Boaventura AC (2016) Plant extracts and essential oils on the control of *Alternaria alternata*, *Alternaria dauci* and on the germination and emergence of carrot seeds (*Daucus carota* L.). Ciênc Rural 46:764–770

de Melo EA, Rosa de Lima RM, Laranjeira D et al (2015) Efficacy of yeast in the biocontrol of bacterial fruit blotch in melon plants. Tropic Plant Pathol 40:56–64. https://doi.org/10.1007/s40858-015-0008-x

Deshmukh MA, Gade RM, Belkar YK, Koche MD (2016) Efficacy of bioagents, biofertilizers and soil amendments to manage root rot in greengram. Legume Res 39:140–144

Deshwal VK, Kumar T, Dubey RC, Maheshwari DK (2006) Long-term effect of *Pseudomonas aeruginosa* GRC1 on yield of subsequent crops of paddy after mustard seed bacterization. Curr Sci 91:423

Dey RKKP, Pal KK, Bhatt DM, Chauhan SM (2004) Growth promotion and yield enhancement of peanut (*Arachis hypogaea* L.) by application of plant growth-promoting rhizobacteria. Microbiol Res 159:371–394. https://doi.org/10.1016/j.micres.2004.08.004

Dhingra OD, Coelho-Netto RA, Rodrigues FÁ et al (2006) Selection of endemic nonpathogenic endophytic *Fusarium oxysporum* from bean roots and rhizosphere competent fluorescent Pseudomonas species to suppress Fusarium-yellow of beans. Biol Control 39:75–86. https://doi.org/10.1016/j.biocontrol.2006.04.006

Diaz-Diaz M, Hurtado de Mendoza DS, Cupull Santana R et al (2018) Actinomycetes, biological alternative on damping-off affectations caused by *Rhizoctonia solani* Kuhn in common bean. Cent Agric 45:5–11

Disi JO, Kloepper JW, Fadamiro HY (2018) Seed treatment of maize with *Bacillus pumilus* strain INR-7 affects host location and feeding by Western corn rootworm, *Diabrotica virgifera virgifera*. J Pest Sci 91:515–522. https://doi.org/10.1007/s10340-017-0927-z

Dodd SL, Stewart A (1992) Biological control of Pythium induced damping-off of beetroot (*Beta vulgaris*) in the glasshouse. N Z J Crop Hortic Sci 20:421–426

Dubey SC (2006) Integrating bioagents with plant extract, oil cake and fungicide in various modes of application for the better management of web blight of urdbean. Arch Phytopathol Plant Prot 39:341–351

Dubey SC, Bhavani R, Singh B (2009) Development of Pusa 5SD for seed dressing and Pusa Biopellet 10G for soil application formulations of *Trichoderma harzianum* and their evaluation for integrated management of dry root rot of mungbean (*Vigna radiata*). Biol Control 50:231–242. https://doi.org/10.1016/j.biocontrol.2009.04.008

Dubey SC, Bhavani R, Singh B (2011) Integration of soil application and seed treatment formulations of Trichoderma species for management of wet root rot of mungbean caused by *Rhizoctonia solani*. Pest Manag Sci 67:1163–1168. https://doi.org/10.1002/ps.2168

Dubey SC, Suresh M, Singh B (2007) Evaluation of Trichoderma species against *Fusarium oxysporum* f. sp. *ciceris* for integrated management of chickpea wilt. Biol Control 40:118–127. https://doi.org/10.1016/j.biocontrol.2006.06.006

Dubey SC, Tripathi A, Singh B (2013) Integrated management of Fusarium wilt by combined soil application and seed dressing formulations of Trichoderma species to increase grain yield of chickpea. Int J Pest Manag 59:47–54

Duczek LJ (1997) Biological control of common root rot in barley by Idriella bolleyi. Can J Plant Pathol 19:402–405

Duffy B (2000) Combination of pencycuron and *Pseudomonas fluorescens* strain 2-79 for integrated control of rhizoctonia root rot and take-all of spring wheat. Crop Prot 19:21–25. https://doi.org/10.1016/S0261-2194(99)00078-2

Dutta S, Morang P, Kumar N, Kumar BD (2014) Two rhizobacterial strains, individually and in interactions with *Rhizobium* sp., enhance fusarial wilt control, growth, and yield in pigeon pea. J Microbiol 52:778–784. https://doi.org/10.1007/s12275-014-3496-3

Egamberdieva D, Kucharova Z, Davranov K et al (2011) Bacteria able to control foot and root rot and to promote growth of cucumber in salinated soils. Biol Fertil Soils 47:197–205. https://doi.org/10.1007/s00374-010-0523-3

Ehteshamul-Haque S, Ghaffar A, Zaki MJ (1990) Biological control of root rot diseases of okra, sunflower, soybean and mungbean. Pak J Bot 22:121–124

El_Komy MH, Hassouna MG, Abou-Taleb EM, et al (2020) A mixture of Azotobacter, Azospirillum, and Klebsiella strains improves root-rot disease complex management and promotes growth in sunflowers in calcareous soil. Eur J Plant Pathol 156:713-726. https://doi.org/10.1007/s10658-019-01921-w

Elanchezhiyan K, Keerthana U, Nagendran K et al (2018) Multifaceted benefits of *Bacillus amyloliquefaciens* strain FBZ24 in the management of wilt disease in tomato caused by *Fusarium oxysporum* f. sp. *lycopersici*. Physiol Mol Plant Pathol 103:92–101. https://doi.org/10.1016/j.pmpp.2018.05.008

Elbadry M, Taha RM, Eldougdoug KA, Gamal-Eldin H (2006) Induction of systemic resistance in faba bean (*Vicia faba* L.) to bean yellow mosaic potyvirus (BYMV) via seed bacterization with plant growth promoting rhizobacteria. J Plant Dis Prot 113:247–251. https://doi.org/10.1007/BF03356189

El-Fiki IAI, Shaheen SIM, Youness HEH, Kamel SM (2014) Evaluation of some bioagents for controlling damping off and root rot diseases of bean (*Phaseolus vulgaris* L.). Egypt J Biol Pest Control 24:275–282

El-Hassan SA, Gowen SR (2006) Formulation and delivery of the bacterial antagonist *Bacillus subtilis* for management of lentil vascular wilt caused by *Fusarium oxysporum* f. sp. *lentis*. J Phytopathol 154:148–155. https://doi.org/10.1111/j.1439-0434.2006.01075.x

El-Hendawy HH, Osman ME, Sorour NM (2005) Biological control of bacterial spot of tomato caused by *Xanthomonas campestris* pv. *vesicatoria* by *Rahnella aquatilis*. Microbiol Res 160:343–352. https://doi.org/10.1016/j.micres.2005.02.008

Elsharkawy MM, El-Sawy MM (2015) Control of bean common mosaic virus by plant extracts in bean plants. Int J Pest Manag 61:54–59

Erdogan O, Benlioglu K (2010) Biological control of Verticillium wilt on cotton by the use of fluorescent *Pseudomonas* spp. under field conditions. Biol Control 53:39–45. https://doi.org/10.1016/j.biocontrol.2009.11.011

Farooq N, Raheem A, Ali B (2014) Waterborne *Escherichia coli*: biosafety and screening as plant growth promoting rhizobacteria. J Pure Appl Microbiol 8:3963–3971

Ferro HM, Souza R, Lelis F et al (2020) Bacteria for cotton plant protection: disease control, crop yield and fiber quality. Rev Caatinga 33:43–53

Flajšman M, Šantavec I, Kolmanič A, Ačko DK (2019) Bacterial seed inoculation and row spacing affect the nutritional composition and agronomic performance of soybean. Int J Plant Prod 13:183–192. https://doi.org/10.1007/s42106-019-00046-8

Fresnedo JA, Kaňková J, Řičica J, Staněk M (1984) Effect of *Agrobacterium radiobacter* and its polysaccharide on emergence and damping-off of tomato plants. Folia microbiol 29:120–126

Frommel MI, Nowak J, Lazarovits G (1993) Treatment of potato tubers with a growth promoting *Pseudomonas* sp.: plant growth responses and bacterium distribution in the rhizosphere. Plant Soil 150:51–60

Fukami J, Nogueira MA, Araujo RS, Hungria M (2016) Accessing inoculation methods of maize and wheat with *Azospirillum brasilense*. Amb Express 6:1–13. https://doi.org/10.1186/s13568-015-0171-y

Fukami J, Ollero FJ, Megías M, Hungria M (2017) Phytohormones and induction of plant-stress tolerance and defense genes by seed and foliar inoculation with *Azospirillum brasilense* cells and metabolites promote maize growth. AMB Express 7:1–13. https://doi.org/10.1186/s13568-017-0453-7

Gagné S, Dehbi L, Le Quéré D et al (1993) Increase of greenhouse tomato fruit yields by plant growth-promoting rhizobacteria (PGPR) inoculated into the peat-based growing media. Soil Biol Biochem 25:269–272

Gajbhiye A, Rai AR, Meshram SU, Dongre AB (2010) Isolation, evaluation and characterization of *Bacillus subtilis* from cotton rhizospheric soil with biocontrol activity against *Fusarium oxysporum*. World J Microbiol Biotechnol 26:1187–1194. https://doi.org/10.1007/s11274-009-0287-9

Gajera HP, Katakpara ZA, Patel SV, Golakiya BA (2016) Antioxidant defense response induced by *Trichoderma viride* against *Aspergillus niger* Van Tieghem causing collar rot in groundnut (*Arachis hypogaea* L.). Microb Pathog 91:26–34. https://doi.org/10.1016/j.micpath.2015.11.010

Gajera HP, Savaliya DD, Patel SV, Golakiya BA (2015) *Trichoderma viride* induces pathogenesis related defense response against rot pathogen infection in groundnut (*Arachis hypogaea* L.). Infec Genet Evol 34:314–325. https://doi.org/10.1016/j.meegid.2015.07.003

Galletti S, Fornasier F, Cianchetta S, Lazzeri L (2015) Soil incorporation of brassica materials and seed treatment with *Trichoderma harzianum*: effects on melon growth and soil microbial activity. Ind Crops Prod 75:73–78. https://doi.org/10.1016/j.indcrop.2015.04.030

Galletti S, Paris R, Cianchetta S (2020) Selected isolates of *Trichoderma gamsii* induce different pathways of systemic resistance in maize upon *Fusarium verticillioides* challenge. Microbiol Res 233:126406. https://doi.org/10.1016/j.micres.2019.126406

Gava CAT, Pinto JM (2016) Biocontrol of melon wilt caused by *Fusarium oxysporum* Schlect f. sp. *melonis* using seed treatment with *Trichoderma* spp. and liquid compost. Biol Control 97:13–20. https://doi.org/10.1016/j.biocontrol.2016.02.010

Geels FP, Lamers JG, Hoekstra O, Schippers B (1986) Potato plant response to seed tuber bacterization in the field in various rotations. Neth J Plant Pathol 92:257–272

Gnanamanickam SS, Candole BL, Mew TW (1992) Influence of soil factors and cultural practice on biological control of sheath blight of rice with antagonistic bacteria. Plant Soil 144:67–75

Goates BJ, Mercier J (2011) Control of common bunt of wheat under field conditions with the biofumigant fungus Muscodor albus. Eur J Plant Pathol 131:403–407. https://doi.org/10.1007/s10658-011-9817-z

Gomes A, Mariano RL, Silveira EB, Mesquita JC (2003) Isolation, selection of bacteria, and effect of *Bacillus* spp. in the production of organic lettuce seedlings. Hortic Bras 21:699–703

Goteti PK, Emmanuel LDA, Desai S, Shaik MHA (2013) Prospective zinc solubilising bacteria for enhanced nutrient uptake and growth promotion in maize (*Zea mays* L.). Int J Microbiol 2013:7. https://doi.org/10.1155/2013/869697

Goudjal Y, Zamoum M, Sabaou N et al (2016) Potential of endophytic *Streptomyces* spp. for biocontrol of Fusarium root rot disease and growth promotion of tomato seedlings. Biocontrol Sci Technol 26:1691–1705. https://doi.org/10.1080/09583157.2016.1234584

Guimaraes GR, Pereira FS, Matos FS et al (2014) Supression of seed borne *Cladosporium herbarum* on common bean seed by *Trichoderma harzianum* and promotion of seedling development. Trop Plant Pathol 39:401–406

Gupta A, Khulbe D, Srinivas P (2014) Induction of systemic resistance in adzuki bean through seed bacterisation. Seed Sci Technol 42:332–343. https://doi.org/10.15258/sst.2014.42.3.03

Gupta C, Dubey R, Maheshwari D (2002) Plant growth enhancement and suppression of *Macrophomina phaseolina* causing charcoal rot of peanut by fluorescent Pseudomonas. Biol Fertil soils 35:399–405. https://doi.org/10.1007/s10526-006-9000-1

Gupta CP, Kumar B, Dubey RC, Maheshwari DK (2006) Chitinase-mediated destructive antagonistic potential of *Pseudomonas aeruginosa* GRC 1 against *Sclerotinia sclerotiorum* causing stem rot of peanut. BioControl 51:821–835. https://doi.org/10.1007/s00374-002-0486-0

Gupta S, Pandey S (2019) ACC deaminase producing bacteria with multifarious plant growth promoting traits alleviates salinity stress in French bean (*Phaseolus vulgaris*) plants. Front Microbiol 10. https://doi.org/10.3389/fmicb.2019.01506

Gupta V, Kumar GN, Buch A (2020) Colonization by multi-potential *Pseudomonas aeruginosa* P4 stimulates peanut (*Arachis hypogaea* L.) growth, defence physiology and root system functioning to benefit the root-rhizobacterial interface. J Plant Physiol 248:153144. https://doi.org/10.1016/j.jplph.2020.153144

Hadar Y, Harman GE, Taylor AG, Norton JM (1983) Effects of pregermination of pea and cucumber seeds and of seed treatment with *Enterobacter cloacae* on rots caused by *Pythium* spp. Phytopathology 73:1322–1325

Halo BA, Al-Yahyai RA, Al-Sadi AM (2018) *Aspergillus terreus* inhibits growth and induces morphological abnormalities in *Pythium aphanidermatum* and suppresses Pythium-induced damping-off of cucumber. Front Microbiol 9. https://doi.org/10.3389/fmicb.2018.00095

Hameeda B, Harini G, Rupela OP et al (2008) Growth promotion of maize by phosphate-solubilizing bacteria isolated from composts and macrofauna. Microbiol Res 163:234–242. https://doi.org/10.1016/j.micres.2006.05.009

Hannan MA, Hasan MM, Hossain I et al (2012) Integrated management of foot rot of lentil using biocontrol agents under field condition. J Microbiol Biotechnol 22:883–888. https://doi.org/10.4014/jmb.1201.01008

Harman GE (1991) Seed treatments for biological control of plant disease. Crop Prot 10:166–171. https://doi.org/10.1016/0261-2194(91)90038-S

Harman GE, Taylor AG, Stasz TE (1989) Combining effective strains of *Trichoderma harzianum* and solid matrix priming to improve biological seed treatments. Plant Dis 73:631–637. https://doi.org/10.1094/PD-73-0631

Harthmann OEL, Mógor ÁF, Wordell Filho JA et al (2009) Seed treatment with rhizobacteria the onion production. Ciência Rural 39:2533–2538

Harvás A, Landa B, Jiménez-Diaz RM (1997) Influence of chickpea genotype and *Bacillus* sp. on protection from Fusarium wilt by seed treatment with nonpathogenic *Fusarium oxysporum*. Eur J Plant Pathol 103:631–642

Holmes KA, Nayagam SD, Craig GD (1998) Factors affecting the control of *Pythium ultimum* damping-off of sugar beet by *Pythium oligandrum*. Plant Pathol 47:516–522

Homma Y, Suzui T (1989) Role of antibiotic production in suppression of radish damping-off by seed bacterization with *Pseudomonas cepacia*. Japanese J Phytopathol 55:643–652

Horuz S, Aysan Y (2018) Biological control of watermelon seedling blight caused by *Acidovorax citrulli* using antagonistic bacteria from the genera *Curtobacterium, Microbacterium* and *Pseudomonas*. Plant Prot Sci 54:138–146. https://doi.org/10.17221/168/2016-PPS

Howell CR, Stipanovic RD, Lumsden RD (1993) Antibiotic production by strains of *Gliocladium virens* and its relation to the biocontrol of cotton seedling diseases. Biocontrol Sci Technol 3:435–441

Howie WJ, Suslow TV (1991) Role of antibiotic biosynthesis in the inhibition of *Pythium ultimum* in the cotton spermosphere and rhizosphere by *Pseudomonas fluorescens*. Mol Plant-Microbe Interact 4:393–399

Hsieh TF, Huang HC, Erickson RS (2005) Biological control of bacterial wilt of bean using a bacterial endophyte, *Pantoea agglomerans*. J Phytopathol 153:608–614

Hu X, Roberts DP, Xie L et al (2014) Formulations of *Bacillus subtilis* BY-2 suppress *Sclerotinia sclerotiorum* on oilseed rape in the field. Biol Control 70:54–64. https://doi.org/10.1016/j.biocontrol.2013.12.005

Hu X, Roberts DP, Xie L et al (2019) Seed treatment containing *Bacillus subtilis* BY-2 in combination with other Bacillus isolates for control of *Sclerotinia sclerotiorum* on oilseed rape. Biol Control 133:50–57. https://doi.org/10.1016/j.biocontrol.2019.03.006

Huang HC, Erickson RS (2007) Effect of seed treatment with *Rhizobium leguminosarum* on pythium damping-off, seedling height, root nodulation, root biomass, shoot biomass, and seed yield of pea and lentil. J Phytopathol 155:31–37. https://doi.org/10.1111/j.1439-0434.2006.01189.x

Huang HC, Erickson RS, Hsieh TF (2007) Control of bacterial wilt of bean (*Curtobacterium flaccumfaciens* pv. *flaccumfaciens*) by seed treatment with *Rhizobium leguminosarum*. Crop Prot 26:1055–1061. https://doi.org/10.1016/j.cropro.2006.09.018

Huber DM, El-Nasshar H, Moore LW et al (1989) Interaction between a peat carrier and bacterial seed treatments evaluated for biological control of the take-all diseases of wheat (*Triticum aestivum* L.). Biol Fertil Soils 8:166–171. https://doi.org/10.1007/BF00257761

Hultberg M, Alsanius B, Sundin P (2000) In vivo and *in vitro* interactions between *Pseudomonas fluorescens* and *Pythium ultimum* in the suppression of damping-off in tomato seedlings. Biol Control 19:1–8. https://doi.org/10.1006/bcon.2000.0840

Hultberg M, Waechter-Kristensen B (1998) Colonization of germinating tomato seeds with the plant growth-promoting rhizobacteria, *Pseudomonas fluorescens* 5.014 and its mutant 5-2/4. Microbiol Res 153:105–111

Jaber LR, Enkerli J (2016) Effect of seed treatment duration on growth and colonization of *Vicia faba* by endophytic *Beauveria bassiana* and *Metarhizium brunneum*. Biol Control 103:187–195. https://doi.org/10.1016/j.biocontrol.2016.09.008

Jambhulkar PP, Sharma P (2014) Development of bioformulation and delivery system of *Pseudomonas fluorescens* against bacterial leaf blight of rice (*Xanthomonas oryzae* pv. *oryzae*). J Environ Biol 35:5

Jayaraj J, Radhakrishnan NV, Kannan R et al (2005) Development of new formulations of Bacillus subtilis for management of tomato damping-off caused by *Pythium aphanidermatum*. Biocontrol Sci Technol 15:55–65. https://doi.org/10.1080/09583150400015920

Jensen B, Knudsen IMB, Jensen DF (2000) Biological seed treatment of cereals with fresh and long-term stored formulations of *Clonostachys rosea*: biocontrol efficacy against *Fusarium culmorum*. Eur J Plant Pathol 106:233–242. https://doi.org/10.1023/A:1008794626600

Jidhu Vaishnavi S, Jeyakumar P (2016) Growth and yield response of cowpea to multiaction bioinoculants. Legum Res 39:962–969. https://doi.org/10.18805/lr.v0iOF.9282

Jiménez JA, Novinscak A, Filion M (2020) *Pseudomonas fluorescens* LBUM677 differentially increases plant biomass, total oil content and lipid composition in three oilseed crops. J Appl Microbiol 128:1119–1127. https://doi.org/10.1111/jam.14536

Joe MM, Islam MR, Karthikeyan B et al (2012) Resistance responses of rice to rice blast fungus after seed treatment with the endophytic *Achromobacter xylosoxidans* AUM54 strains. Crop Prot 42:141–148. https://doi.org/10.1016/j.cropro.2012.07.006

Johansson PM, Johnsson L, Gerhardson B (2003) Suppression of wheat-seedling diseases caused by *Fusarium culmorum* and *Microdochium nivale* using bacterial seed treatment. Plant Pathol 52:219–227. https://doi.org/10.1046/j.1365-3059.2003.00815.x

Johnsson L, H"okeberg M, Gerhardson B (1998) Performance of the *Pseudomonas chlororaphis* biocontrol agent MA 342 against cereal seed-borne diseases in field experiments. Eur J Plant Pathol 104:701–711. https://doi.org/10.1023/A:1008632102747

Joseph AR, Kavimandan SK, Tilak KV, Nain L (2014) Response of canola and wheat to amendment of pyrite and sulphur-oxidizing bacteria in soil. Arch Agron Soil Sci 60:367–375. https://doi.org/10.1080/03650340.2013.799275

Joshi KK, Kumar V, Dubey RC et al (2006) Effect of chemical fertilizer-adaptive variants, *Pseudomonas aeruginosa* GRC 2 and *Azotobacter chroococcum* AC 1, on *Macrophomina phaseolina* causing charcoal rot of *Brassica juncea*. Korean J Environ Agric 25:228–235

Junges E, Muniz MF, Mezzomo R et al (2016) Trichoderma spp. na produçao de mudas de espécies florestais. Floresta e Ambient 23:237–244

Kala C, Gangopadhyay S, Godara SL (2016) Eco-friendly management of wilt caused by *Fusarium oxysporum* f. sp. *ciceri* in chickpea. Legum Res 39:129–134. https://doi.org/10.18805/lr.v0iOF.6789

Kamalnath M, Rao MS, Umamaheswari R (2019) Rhizophere engineering with beneficial microbes for growth enhancement and nematode disease complex management in gherkin (*Cucumis anguria* L.). Sci Hortic (Amsterdam) 257. https://doi.org/10.1016/j.scienta.2019.108681

Kanižai G, Milaković Z, Šeput M, Al E (2007) Effect of lucerne seed bacterization (*Medicago sativa* L.) on yield components in ecological cultivation. Cereal Res Commun 35:577–580. https://doi.org/10.1556/CRC.35.2007.2.103

Kavitha R, Umesha S (2007) Prevalence of bacterial spot in tomato fields of Karnataka and effect of biological seed treatment on disease incidence. Crop Prot 26:991–997. https://doi.org/10.1016/j.cropro.2006.09.007

Kay SJ, Stewart A (1994) Evaluation of fungal antagonists for control of onion white rot in soil box trials. Plant Pathol 43:371–377

Kazmar ER, Goodman RM, Grau CR et al (2000) Regression analyses for evaluating the influence of Bacillus cereus on alfalfa yield under variable disease intensity. Phytopathology 90:657–665. https://doi.org/10.1094/PHYTO.2000.90.6.657

Keinath AP, Batson WE Jr, Caceres J, Elliott ML et al (2000) Evaluation of biological and chemical seed treatments to improve stand of snap bean across the southern United States. Crop Prot 19:501–509. https://doi.org/10.1016/S0261-2194(00)00047-8

Keyser CA, Jensen B, Meyling NV (2016) Dual effects of *Metarhizium* spp. and *Clonostachys rosea* against an insect and a seed-borne pathogen in wheat. Pest Manag Sci 72:517–526. https://doi.org/10.1002/ps.4015

Khabbaz SE, Abbasi PA (2014) Isolation, characterization, and formulation of antagonistic bacteria for the management of seedlings damping-off and root rot disease of cucumber. Can J Microbiol 60:25–33. https://doi.org/10.1139/cjm-2013-0675

Khalili E, Sadravi M, Naeimi S, Khosravi V (2012) Biological control of rice brown spot with native isolates of three Trichoderma species. Brazilian J Microbiol 43:297–305. https://doi.org/10.1590/S1517-83822012000100035

Khan MQ, Abbasi MW, Zaki MJ, Khan SA (2010) Evaluation of *Bacillus thuringiensis* isolates against root-knot nematodes following seed application in okra and mungbean. Pak J Bot 42:2903–2910

Khan MR, Anwer MA, Shahid S (2011) Management of gray mold of chickpea, *Botrytis cinerea* with bacterial and fungal biopesticides using different modes of inoculation and application. Biol Control 57:13–23. https://doi.org/10.1016/j.biocontrol.2011.01.004

Khan MR, Ashraf S, Rasool F et al (2014) Field performance of Trichoderma species against wilt disease complex of chickpea caused by *Fusarium oxysporum* f. sp. *ciceri* and *Rhizoctonia solani*. Turkish J Agric For 38:447–454

Khan MR, Khan SM, Mohiddin FA (2004) Biological control of Fusarium wilt of chickpea through seed treatment with the commercial formulation of *Trichoderma harzianum* and/or *Pseudomonas fluorescens*. Phytopathol Mediterr 43:20–25

Khan MR, Mohiddin FA, Ahamad F (2018a) Inoculant rhizobia suppressed root-knot disease, and enhanced plant productivity and nutrient uptake of some field-grown food legumes. Acta Agric Scand Sect B—Soil Plant Sci 68:166–174. https://doi.org/10.1080/09064710.2017.1374448

Khan MR, Mohidin FA, Khan U, Ahamad F (2016) Native *Pseudomonas* spp. suppressed the root-knot nematode in in vitro and in vivo, and promoted the nodulation and grain yield in the field grown mungbean. Biol Control 101:159–168. https://doi.org/10.1016/j.biocontrol.2016.06.012

Khan N, Martínez-Hidalgo P, Ice TA et al (2018b) Antifungal activity of Bacillus species against Fusarium and analysis of the potential mechanisms used in biocontrol. Front Microbiol 9. https://doi.org/10.3389/fmicb.2018.02363

Khandare RN, Chandra R, Pareek N, Raverkar KP (2020) Carrier-based and liquid bioinoculants of Azotobacter and PSB saved chemical fertilizers in wheat (*Triticum aestivum* L.) and enhanced soil biological properties in Mollisols. J Plant Nutr 43:36–50. https://doi.org/10.1080/01904167.2019.1659333

King EB, Parke JL (1993) Biocontrol of Aphanomyces root rot and Pythium damping-off by *Pseudomonas cepacia* AMMD on four pea cultivars. Plant Dis 77:1185–1188

Kishore GK, Pande S, Podile AR (2005a) Biological control of collar rot disease with broad-spectrum antifungal bacteria associated with groundnut. Can J Microbiol 51:123–132

Kishore GK, Pande S, Podile AR (2005b) Phylloplane bacteria increase seedling emergence, growth and yield of field-grown groundnut (*Arachis hypogaea* L.). Lett Appl Microbiol 40:260–268. https://doi.org/10.1111/j.1472-765X.2005.01664.x

Kishore GK, Pande S, Podile AR (2006) *Pseudomonas aeruginosa* GSE 18 inhibits the cell wall degrading enzymes of *Aspergillus niger* and activates defence-related enzymes of groundnut in control of collar rot disease. Australas Plant Pathol 35:259–263. https://doi.org/10.1139/w04-119

Kleifeld O, Chet I (1992) *Trichoderma harzianum*—interaction with plants and effect on growth response. Plant Soil 144:267–272

Koch E, Kempf HJ, Hessenm"uller A (1998) Characterization of the biocontrol activity and evaluation of potential plant growth-promoting properties of selected rhizobacteria. J Plant Dis Prot 105:567–580

Koch E, Schmitt A, Stephan D et al (2010) Evaluation of non-chemical seed treatment methods for the control of *Alternaria dauci* and *A. radicina* on carrot seeds. Eur J Plant Pathol 127:99–112. https://doi.org/10.1007/s10658-009-9575-3

Koch E, Weil B, Wächter R et al (2006) Evaluation of selected microbial strains and commercial alternative products as seed treatments for the control of *Tilletia tritici*, *Fusarium culmorum*, *Drechslera graminea* and *D. teres*. J Plant Dis Prot 113:150–158. https://doi.org/10.1007/BF03356172

Kokalis-Burelle N (2015) *Pasteuria penetrans* for control of *Meloidogyne incognita* on tomato and cucumber, and M. arenaria on snapdragon. J Nematol 47:3

Kommedahl T, Windels CE (1978) Evaluation of biological seed treatment for controlling root diseases of pea. Phytopathology 68:1087–1095. https://doi.org/10.1094/Phyto-68-1087

Kotasthane AS, Agrawal T, Zaidi NW, Singh US (2017) Identification of siderophore producing and cynogenic fluorescent Pseudomonas and a simple confrontation assay to identify potential bio-control agent for collar rot of chickpea. Biotech 7:1–8. https://doi.org/10.1007/s13205-017-0761-2

Krishnamurthy K, Gnanamanickam SS (1998) Biological control of rice blast by *Pseudomonas fluorescens* strain Pf7–14: evaluation of a marker gene and formulations. Biol Control 13:158–165

Kristek S, Kristek A, Guberac V, Tokić G (2006) Influence of sugar beet seed treatment with *Pseudomonas fluorescens* and low fungicide doses on infection with Pythium and plant yield and quality. J Phytopathol 154:622–625

Król P, Adamska J, Kępczyńska E (2014) Enhancement of *Festuca rubra* L. germination and seedling growth by seed treatment with pathogenic *Agrobacterium rhizogenes*. Acta Physiol Plant 36:3263–3274. https://doi.org/10.1007/s11738-014-1692-8

Kumar A (2014) Integrated crop disease management in arid Rajasthan: a synthesis of indigenous knowledge with biocontrol. Curr Sci 107:1393–1399

Kumar BD (1998) Disease suppression and crop improvement through fluorescent pseudomonads isolated from cultivated soils. World J Microbiol Biotechnol 14:735–741

Kumar BD (1999) Fusarial wilt suppression and crop improvement through two rhizobacterial strains in chick pea growing in soils infested with *Fusarium oxysporum* f. sp. *ciceris*. Biol Fertil Soils 29:87–91

Kumar BD, Dube HC (1992) Seed bacterization with a fluorescent Pseudomonas for enhanced plant growth, yield and disease control. Soil Biol Biochem 24:539–542

Kumar V, Singh P, Jorquera MA et al (2013) Isolation of phytase-producing bacteria from Himalayan soils and their effect on growth and phosphorus uptake of Indian mustard (*Brassica juncea*). World J Microbiol Biotechnol 29:1361–1369. https://doi.org/10.1007/s11274-013-1299-z

Kundu BS, Nandal K, Tiwari M, Tomar M (2006) Establishment and influence of phosphate solubilizing bacteria on pearl millet. Indian J plant Physiol 11:2

Kuz'mina LY, Melent'ev AI (2003) The effect of seed bacterization by Bacillus Cohn bacteria on their colonization of the spring wheat rhizosphere. Microbiology 72:230–235. https://doi.org/10.1023/A:1023280300908

Larkin RP (2016) Impacts of biocontrol products on Rhizoctonia disease of potato and soil microbial communities, and their persistence in soil. Crop Prot 90:96–105. https://doi.org/10.1016/j.cropro.2016.08.012

Leggett M, Newlands NK, Greenshields D et al (2015) Maize yield response to a phosphorus-solubilizing microbial inoculant in field trials. J Agric Sci 153:1464–1478. https://doi.org/10.1017/S0021859614001166

Leisso RS, Miller PR, Burrows ME (2009) The influence of biological and fungicidal seed treatments on chickpea (*Cicer arietinum*) damping off. Can J Plant Pathol 31:38–46. https://doi.org/10.1080/07060660909507570

Lestari SM, Hidayat SH, Widodo W (2018) Determination of endophytic fungi as induce resistance agent of chilli pepper against pepper yellow leaf curl disease. Agrivita, J Agric Sci 40:249–256. https://doi.org/10.13080/z-a.2019.106.031

Liang XY, Huang HC, Yanke LJ, Kozub GC (1996) Control of damping-off of safflower by bacterial seed treatment. Can J Plant Pathol 18:43–49

Liatukas Ž, Suproniene S, Ruzgas V, Leistrumaite A (2009) Effects of organic seed treatment methods on spring barley seed quality, crop, productivity and disease incidence. Zemdirbyste-Agriculture. https://doi.org/10.13080/Z-A.2019.106.031

Lizárraga-Sánchez GJ, Leyva-Madrigal KY, Sánchez-Peña P, Al E (2015) *Bacillus cereus sensu lato* strain B25 controls maize stalk and ear rot in Sinaloa, Mexico. F Crop Res 25:11–21. https://doi.org/10.1016/j.fcr.2015.02.015

Lopez-Reyes JG, Gilardi GG, Garibaldi A, Gullino ML (2014) Efficacy of bacterial and fungal biocontrol agents as seed treatments against *Fusarium oxysporum* f. sp. lactucae on lettuce. J Plant Pathol 96:535–539. https://doi.org/10.4454/JPP.V96I3.024

Lopez-Reyes JG, Gilardi G, Garibaldi A, Gullino ML (2016) *In vivo* evaluation of essential oils and biocontrol agents combined with hot water treatments on carrot seeds against *Alternaria radicina*. J Phytopathol 164:131–135. https://doi.org/10.1111/jph.12400

Lowman JS, Lava-Chavez A, Kim-Dura S et al (2015) Switchgrass field performance on two soils as affected by bacterization of seedlings with *Burkholderia phytofirmans* strain PsJN. BioEnergy Res 8:440–449. https://doi.org/10.1007/s12155-014-9536-3

Müller TM, Sandini IE, Rodrigues JD et al (2016) Combination of inoculation methods of *Azospirilum brasilense* with broadcasting of nitrogen fertilizer increases corn yield. Ciência Rural 46:210–215

Maheshwari DK, Dubey RC, Aeron A et al (2012) Integrated approach for disease management and growth enhancement of *Sesamum indicum* L. utilizing *Azotobacter chroococcum* TRA2 and chemical fertilizer. World J Microbiol Biotechnol 28:3015–3024. https://doi.org/10.1007/s11274-012-1112-4

Malik DK, Sindhu SS (2011) Production of indole acetic acid by *Pseudomonas* sp.: effect of coinoculation with *Mesorhizobium* sp. Cicer nodulation plant growth chickpea (*Cicer arietinum*). Physiol Mol Biol Plants 17:25–32

Mangwende E, Kritzinger Q, Aveling TAS (2019) Control of Alternaria leaf spot of coriander in organic farming. Eur J Plant Pathol 154:575–584. https://doi.org/10.1007/s10658-019-01682-6

Manhas RK, Kaur T (2016) Biocontrol potential of *Streptomyces hydrogenans* strain DH16 toward *Alternaria brassicicola* to control damping off and black leaf spot of *Raphanus sativus*. Front Plant Sci 7. https://doi.org/10.3389/fpls.2016.01869

Mao W, Lewis JA, Hebbar PK, Lumsden RD (1997) Seed treatment with a fungal or a bacterial antagonist for reducing corn damping-off caused by species of *Pythium* and *Fusarium*. Plant Dis 81:450–454. https://doi.org/10.1094/PDIS.1997.81.5.450

Mao W, Lewis JA, Lumsden RD, Hebbar KP (1998a) Biocontrol of selected soilborne diseases of tomato and pepper plants. Crop Prot 17:535–542

Mao W, Lumsden RD, Lewis JA, Hebbar PK (1998b) Seed treatment using pre-infiltration and biocontrol agents to reduce damping-off of corn caused by species of *Pythium* and *Fusarium*. Plant Dis 82:294–299. https://doi.org/10.1094/PDIS.1998.82.3.294

Marroni IV, Moura AB, Ueno B (2012) Chemical and biological treatments of castor bean seeds: effects on germination, emergence and associated microorganisms. Rev. Bras. Sementes 34:21–28

Martinez-Álvarez JC, Castro-Martinez C, Sánchez-Peña P, Al E (2016) Development of a powder formulation based on *Bacillus cereus* sensu lato strain B25 spores for biological control of *Fusarium verticillioides* in maize plants. World J Microbiol Biotechnol 32:5. https://doi.org/10.1007/s11274-015-2000-5

Martins SA, Schurt DA, Seabra SS et al (2018) Common bean (*Phaseolus vulgaris* L.) growth promotion and biocontrol by rhizobacteria under *Rhizoctonia solani* suppressive and conducive soils. Appl Soil Ecol 127:129–135. https://doi.org/10.1016/j.apsoil.2018.03.007

Martins SJ, de Medeiros FHV, de Souza RM et al (2013) Biological control of bacterial wilt of common bean by plant growth-promoting rhizobacteria. Biol Control 66:65–71. https://doi.org/10.1016/j.biocontrol.2013.03.009

Masangwa JIG, Kritzinger Q, Aveling TAS (2017) Germination and seedling emergence responses of common bean and cowpea to plant extract seed treatments. J Agric Sci 155:1. https://doi.org/10.1017/S0021859616000113

Mastouri F, Björkman T, Harman GE (2010) Seed treatment with *Trichoderma harzianum* alleviates biotic, abiotic, and physiological stresses in germinating seeds and seedlings. Phytopathology 100:1213–1221. https://doi.org/10.1094/PHYTO-03-10-0091

Mathre D, Johnston RH, Callan NW et al (1995) Combined biological and chemical seed treatments for control of two seedling diseases of sh2 sweet corn. Plant Dis 79:1145–1148

Mathre DE, Callan NW, Johnston RH et al (1994) Factors influencing the control of *Pythium ultimum*-induced seed decay by seed treatment with *Pseudomonas aureofaciens* AB254. Crop Prot 13:301–307

Mazur VA, Pantsyreva HV, Mazur KV, Didur IM (2019) Influence of the assimilation apparatus and productivity of white lupine plants. Agron Res 2019. https://doi.org/10.15159/ar.19.024

Mbega ER, Mabagala RB, Mortensen CN, Wulff EG (2012) Evaluation of essential oils as seed treatment for the control of *Xanthomonas* spp. associated with the bacterial leaf spot of tomato in Tanzania. J Plant Pathol:273–281. https://doi.org/10.4454/JPP.FA.2012.024

Meena B, Radhajeyalakshmi R, Marimuthu T et al (2002) Biological control of groundnut late leaf spot and rust by seed and foliar applications of a powder formulation of *Pseudomonas fluorescens*. Biocontrol Sci Technol 12:195–204. https://doi.org/10.1080/09583150120124450

Meena PD, Gour RB, Gupta JC et al (2013) Non-chemical agents provide tenable, eco-friendly alternatives for the management of the major diseases devastating Indian mustard (*Brassica juncea*) in India. Crop Prot 53:169–174. https://doi.org/10.1016/j.cropro.2013.07.006

Mercado-Flores Y, Cárdenas-Álvarez IO, Rojas-Olvera AV et al (2014) Application of *Bacillus subtilis* in the biological control of the phytopathogenic fungus *Sporisorium reilianum*. Biol Control 76:36–40. https://doi.org/10.1016/j.biocontrol.2014.04.011

Mertz LM, Henning FA, Zimmer PD (2009) Bioprotectors and chemical fungicides in the treatment of soybean seeds. Ciência Rural 39:13–18

Mew TW, Rosales AM (1986) Bacterization of rice plants for control of sheath blight caused by Rhizoctonia solani. Phytopathology 76: 1260–1264

Meyer SL, Massoud SI, Chitwood DJ, Roberts DP (2000) Evaluation of *Trichoderma virens* and *Burkholderia cepacia* for antagonistic activity against root-knot nematode, *Meloidogyne incognita*. Nematology 2:871–879

Meyer SL, Roberts DP, Chitwood DJ et al (2001) Application of *Burkholderia cepacia* and *Trichoderma virens*, alone and in combinations, against *Meloidogyne incognita* on bell pepper. Nematropica 31:75–86

Minaeva OM, Akimova EE, Tereshchenko NN et al (2019) Pseudomonads associated with soil lumbricides as promising agents in root rot biocontrol for spring grain crops. Agric Biol 54:91–100

Mishra PK, Mishra S, Selvakumar G et al (2008) Characterisation of a psychrotolerant plant growth promoting *Pseudomonas* sp. strain PGERs17 (MTCC 9000) isolated from North Western Indian Himalayas. Ann Microbiol 58:561–568

Mishra PK, Mukhopadhyay AN, Fox RTV (2000) Integrated and biological control of gladiolus corm rot and wilt caused by *Fusarium oxysporum* f. sp. *gladioli*. Ann Appl Biol 137:361–364. https://doi.org/10.1007/BF03175558

Moënne-Loccoz Y, Powell J, Higgins P et al (1998) Effect of the biocontrol agent *Pseudomonas fluorescens* F113 released as sugarbeet inoculant on the nutrient contents of soil and foliage of a red clover rotation crop. Biol Fertil soils 27:380–385

Moharam MH, Stephan D, Koch E (2018) Evaluation of plant-derived preparations and microorganisms as seed treatments for control of covered kernel smut of sorghum (*Sporisorium sorghi*). J Plant Dis Prot 125:159–166. https://doi.org/10.1007/s41348-017-0123-7

Mohiddin FA, Khan MR (2019) Efficacy of newly developed biopesticides for the management of wilt disease complex of chickpea (*Cicer arietinum* L.). Legum Res Int J 42:550–556

More YD, Gade RM, Shitole AV (2017) *In vitro* antifungal activity of *Aegle marmelos*, *Syzygium cumini* and *Pongamia pinnata* extracts against *Fusarium oxysporum* f. sp. *cicero*. Indian J Pharm Sci 79:457–462

Moussa TAA, Almaghrabi OA, Abdel-Moneim TS (2013) Biological control of the wheat root rot caused by *Fusarium graminearum* using some PGPR strains in Saudi Arabia. Ann Appl Biol 163:72–81

Munareto JD, Martin TN, Muller TM et al (2018) Compatibility of *Azospirillum brasilense* with fungicide and insecticide and its effects on the physiological quality of wheat seeds. Sem Ciênc Agr Lond 39:855–864

Muthukumar A, Eswaran A, Nakkeeran S, Sangeetha G (2010) Efficacy of plant extracts and biocontrol agents against *Pythium aphanidermatum* inciting chilli damping-off. Crop Prot 29:1483–1488. https://doi.org/10.1016/j.cropro.2010.08.009

Nagachandrabose S (2020) Management of potato cyst nematodes using liquid bioformulations of *Pseudomonas fluorescens*, *Purpureocillium lilacinum* and *Trichoderma viride*. Potato Res pp: 1–18. https://doi.org/10.1007/s11540-020-09452-2

Nagarajkumar M, Jayaraj J, Muthukrishnan S et al (2005) Detoxification of oxalic acid by *Pseudomonas fluorescens* strain PfMDU2: implications for the biological control of rice sheath blight caused by *Rhizoctonia solani*. Microbiol Res 160:291–298. https://doi.org/10.1016/j.micres.2005.02.002

Nagendran K, Karthikeyan G, Faisal M et al (2014) Exploiting endophytic bacteria for the management of sheath blight disease in rice. Biol Agric Hortic 30:8–23

Nandakumar R, Babu S, Viswanathan R et al (2001) A new bioformulation containing plant growth promoting rhizobacterial mixture for the management of sheath blight and enhanced grain yield in rice. Biocontrol 46:493–510. https://doi.org/10.1023/A:1014131131808

Naraghi L, Heydari A, Rezaee S, Razavi M (2012) Biocontrol agent *Talaromyces flavus* stimulates the growth of cotton and potato. J Plant Growth Regul 31:471–477. https://doi.org/10.1007/s00344-011-9256-2

Narasimhamurthy K, Soumya K, Udayashankar AC et al (2019) Elicitation of innate immunity in tomato by salicylic acid and *Amomum nilgiricum* against *Ralstonia solanacearum*. Biocatal Agric Biotechnol 22. https://doi.org/10.1016/j.bcab.2019.101414

Nautiyal CS (1997) Selection of chickpea-rhizosphere-competent *Pseudomonas fluorescens* NBRI1303 antagonistic to *Fusarium oxysporum* f. sp. *ciceri*, *Rhizoctonia bataticola* and *Pythium* sp. Curr Microbiol 35:52–58

Naveenkumar R, Muthukumar A, Sangeetha G, Mohanapriya R (2017) Developing eco-friendly biofungicide for the management of major seed borne diseases of rice and assessing their physical stability and storage life. C R Biol 340:214–225. https://doi.org/10.1016/j.crvi.2017.03.001

Nehra V, Saharan BS, Choudhary M (2016) Evaluation of *Brevibacillus brevis* as a potential plant growth promoting rhizobacteria for cotton (*Gossypium hirsutum*) crop. Springerplus 5:948. https://doi.org/10.1186/s40064-016-2584-8

Nejad P, Johnson PA (2000) Endophytic bacteria induce growth promotion and wilt disease suppression in oilseed rape and tomato. Biol Control 18:208–215. https://doi.org/10.1006/bcon.2000.0837

Nelson EB (1988) Biological control of *Pythium* seed rot and preemergence damping-off with *Enterobacter cloacae* and *Erwinia herbicola* applied as seed treatments. Plant Dis 72:140–142

Nguefack J, Wulff GE, Dongmo JBL et al (2013) Effect of plant extracts and an essential oil on the control of brown spot disease, tillering, number of panicles and yield increase in rice. Eur J plant Pathol 137: 871–882. https://doi.org/10.1007/s10658-013-0298-0

Niranjana SR, Lalitha S, Hariprasad P (2009) Mass multiplication and formulations of biocontrol agents for use against fusarium wilt of pigeonpea through seed treatment. Int J Pest Manag 55:317–324. https://doi.org/10.1080/09670870902919147

Noel GR (1990) Inability of a seed treatment with *Pseudomonas cepacia* to control *Heterodera glycines* on soybean. J Nematol 22:4

Nunes HT, Monteiro AC, Pomela AWV (2010) Use of microbial and chemical agents to control *Meloidogyne incognita* in soybean. Acta Sci Agron 32:403–409. https://doi.org/10.4025/actasciagron.v32i3.2166

Omomowo IO, Fadiji AE, Omomowo OI (2018) Assessment of bioefficacy of *Glomus versiforme* and *Trichoderma harzianum* in inhibiting powdery mildew disease and enhancing the growth of cowpea. Ann Agric Sci 63:9–17. https://doi.org/10.1016/j.aoas.2018.03.001

Oostendorp M, Sikora RA (1989) Seed treatment with antagonistic rhizobacteria for the suppression of *Heterodera schachtii* early root infection of sugar beet. Rev Nematol 12:77–83

Özer N (2011) Screening for fungal antagonists to control black mold disease and to induce the accumulation of antifungal compounds in onion after seed treatment. BioControl 56:237–247. https://doi.org/10.1007/s10526-010-9326-6

Palma CAV, Burrows RPM, González MG et al (2019) Integration between *Pseudomonas protegens* strains and fluquinconazole for the control of take-all in wheat. Crop Prot 121:163–172. https://doi.org/10.1016/j.cropro.2019.03.020

Pandya U, Saraf M (2015) Isolation and identification of allelochemicals produced by *B. sonorensis* for suppression of charcoal rot of *Arachis hypogaea* L. J Basic Microbiol 55:635–644

Parikh L, Adesemoye AO (2018) Impact of delivery method on the efficacy of biological control agents and the virulence of Fusarium root rot pathogens in the greenhouse. Biocontrol Sci Technol 28:1191–1202. https://doi.org/10.1080/09583157.2018.1520198

Patel KS, Naik JH, Chaudhari S, Amaresan N (2017) Characterization of culturable bacteria isolated from hot springs for plant growth promoting traits and effect on tomato (*Lycopersicon esculentum*) seedling. C R Biol 340:244–249. https://doi.org/10.1016/j.crvi.2017.02.005

Pathak DV, Kumar M, Sharma SK et al (2007) Crop improvement and root rot suppression by seed bacterization in chickpea. Arch Agron Soil Sci 53:287–292. https://doi.org/10.1080/03650340601124909

Peix A, Mateos PF, Rodriguez-Barrueco C et al (2001) Growth promotion of common bean (*Phaseolus vulgaris* L.) by a strain of *Burkholderia cepacia* under growth chamber conditions. Soil Biol Biochem 33:1927–1935. https://doi.org/10.1016/S0038-0717(01)00119-5

Peng G, McGregor L, Lahlali R et al (2011) Potential biological control of clubroot on canola and crucifer vegetable crops. Plant Pathol 60:566–574

Pengnoo A, Wiwattanapattapee R, Chumthong A, Kanjanamaneesathian M (2006) Bacterial antagonist as seed treatment to control leaf blight disease of bambara groundnut (*Vigna subterranea*). World J Microbiol Biotechnol 22:9–14. https://doi.org/10.1007/s11274-005-2820-9

Pereira P, Nesci A, Castillo C, Etcheverry M (2010) Impact of bacterial biological control agents on fumonisin B1 content and *Fusarium verticillioides* infection of field-grown maize. Biol Control 53:258–266. https://doi.org/10.1016/j.biocontrol.2010.02.001

Perelló AE, Dal Bello GM (2011) Suppression of tan spot and plant growth promotion of wheat by synthetic and biological inducers under field conditions. Ann Appl Biol 158:267–274. https://doi.org/10.1111/j.1744-7348.2011.00460.x

Pill WG, Collins CM, Gregory N, Evans TA (2011) Application method and rate of Trichoderma species as a biological control against *Pythium aphanidermatum* (Edson) Fitzp. in the production of microgreen table beets (*Beta vulgaris* L.). Sci Hortic (Amsterdam) 129:914–918. https://doi.org/10.1016/j.scienta.2011.05.018

Podile AR (1994) Survival of *Bacillus subtilis* AF 1 in the bacterized peanut rhizosphere and its influence on native microflora and seedling growth. World J Microbiol Biotechnol 10:700–703

Podile AR, Dube HC (1988) Plant growth-promoting activity of *Bacillus subtilis* AF1. Curr Sci 57:183–186

Podile AR, Laxmi VDV (1998) Seed bacterization with *Bacillus subtilis* AF 1 increases phenylalanine ammonia-lyase and reduces the incidence of fusarial wilt in pigeonpea. J Phytopathol 146:255–259

Postma J, Nijhuis EH (2019) *Pseudomonas chlororaphis* and organic amendments controlling Pythium infection in tomato. Eur J Plant Pathol 154:91–107. https://doi.org/10.1007/s10658-019-01743-w

Prasad RD, Rangeshwaran R, Hegde SV, Anuroop CP (2002) Effect of soil and seed application of *Trichoderma harzianum* on pigeonpea wilt caused by *Fusarium udum* under field conditions. Crop Prot 21:293–297. https://doi.org/10.1016/S0261-2194(01)00100-4

Prasanna R, Kanchan A, Kaur S et al (2016) Chrysanthemum growth gains from beneficial microbial interactions and fertility improvements in soil under protected cultivation. Hortic Plant J 2:229–239. https://doi.org/10.1016/j.hpj.2016.08.008

Rabindran R, Vidhyasekaran P (1996) Development of a formulation of *Pseudomonas fluorescens* PfALR2 for management of rice sheath blight. Crop Prot 15:715–721

Rahman M, Punja ZK (2007) Biological control of damping-off on American ginseng (*Panax quinquefolius*) by *Clonostachys rosea* f. *catenulata* (= *Gliocladium catenulatum*). Can J plant Pathol 29:203–207. https://doi.org/10.1080/07060660709507458

Raj SN, Chaluvaraju G, Amruthesh KN et al (2003a) Induction of growth promotion and resistance against downy mildew on pearl millet (*Pennisetum glaucum*) by rhizobacteria. Plant Dis 87:380–384. https://doi.org/10.1094/PDIS.2003.87.4.380

Raj SN, Deepak SA, Basavaraju P et al (2003b) Comparative performance of formulations of plant growth promoting rhizobacteria in growth promotion and suppression of downy mildew in pearl millet. Crop Prot 22:579–588. https://doi.org/10.1016/S0261-2194(02)00222-3

Rajkumar M, Lee KJ, Freitas H (2008) Effects of chitin and salicylic acid on biological control activity of *Pseudomonas* spp. against damping off of pepper. South African J Bot 74:268–273. https://doi.org/10.1016/j.sajb.2007.11.014

Ramamoorthy V, Samiyappan T, Raguchander R (2002) Enhancing resistance of tomato and hot pepper to Pythium diseases by seed treatment with fluorescent pseudomonads. Eur J Plant Pathol 108:429–441. https://doi.org/10.1023/A:1016062702102

Rani A, Souche YS, Goel R (2009) Comparative assessment of in situ bioremediation potential of cadmium resistant acidophilic *Pseudomonas putida* 62BN and alkalophilic *Pseudomonas monteilli* 97AN strains on soybean. Int Biodeterior Biodegradation 63:62–66. https://doi.org/10.1016/j.ibiod.2008.07.002

Rao MS, Kamalnath M, Umamaheswari R et al (2017) *Bacillus subtilis* IIHR BS-2 enriched vermicompost controls root knot nematode and soft rot disease complex in carrot. Sci Hortic (Amsterdam) 218:56–62. https://doi.org/10.1016/j.scienta.2017.01.051

Rao VK, Krishnappa K (1995) Integrated management of Meloidogyne incognita-Fusarium oxysporum f. sp. ciceri wilt disease complex in chickpea. Int J Pest Manag 41:234–237

Raupach GS, Liu L, Murphy JF et al (1996) Induced systemic resistance in cucumber and tomato against cucumber mosaic cucumovirus using plant growth-promoting rhizobacteria (PGPR). Plant Dis 80:891–894

Reddy MS, Rahe JE (1989) Growth effects associated with seed bacterization not correlated with populations of *Bacillus subtilis* inoculant in onion seedling rhizospheres. Soil Biol Biochem 21:373–378

Reznikov S, Vellicce GR, González V et al (2016) Evaluation of chemical and biological seed treatments to control charcoal rot of soybean. J Gen Plant Pathol 82:273–280. https://doi.org/10.1007/s10327-016-0669-4

Rioux S, Pouleur S, Randall P et al (2016) Efficacy of acetic acid vapours and dry heat to control *Fusarium graminearum* and *Bipolaris sorokiniana* in barley and wheat seeds. Phytoprotection 96:1–11. https://doi.org/10.7202/1037531ar

Roberti R, Flori P, Pisi A et al (2000) Evaluation of biological seed treatment of wheat for the control of seed-borne *Fusarium culmorum*. J Plant Dis Prot 107:484–493

Roberts DP, Lakshman DK, Maul JE et al (2014) Control of damping-off of organic and conventional cucumber with extracts from a plant-associated bacterium rivals a seed treatment pesticide. Crop Prot 65:86–94. https://doi.org/10.1016/j.cropro.2014.07.009

Roberts DP, Lakshman DK, McKenna LF et al (2016) Seed treatment with ethanol extract of *Serratia marcescens* is compatible with trichoderma isolates for control of damping-off of cucumber caused by *Pythium ultimum*. Plant Dis 100:1278–1287. https://doi.org/10.1094/PDIS-09-15-1039-RE

Roberts DP, Lohrke SM, Meyer SLF et al (2005) Biocontrol agents applied individually and in combination for suppression of soilborne diseases of cucumber. Crop Prot 24:141–155. https://doi.org/10.1016/j.cropro.2004.07.004

Roberts DP, McKenna LF, Buyer JS (2017) Consistency of control of damping-off of cucumber is improved by combining ethanol extract of *Serratia marcescens* with other biologically based technologies. Crop Prot 96:59–67. https://doi.org/10.1016/j.cropro.2017.01.007

Roberts DP, McKenna LF, Lakshman DK et al (2007) Suppression of damping-off of cucumber caused by *Pythium ultimum* with live cells and extracts of *Serratia marcescens* N4-5. Soil Biol Biochem 39: 2275–2288. https://doi.org/10.1016/j.soilbio.2007.03.029

Rosales AM, Mew TW (1997) Suppression of *Fusarium moniliforme* in rice by rice-associated antagonistic bacteria. Plant Dis 81:49–52

Rosales AM, Vantomme R, Swings J et al (1993) Identification of some bacteria from paddy antagonistic to several rice fungal pathogens. J Phytopathol 138:189–208

Roychowdhury R, Qaiser TF, Mukherjee P, Roy M (2019) Isolation and characterization of a *Pseudomonas aeruginosa* strain PGP for plant growth promotion. Proc Natl Acad Sci India Sect B Biol Sci 89: 353–360. https://doi.org/10.1007/s40011-017-0946-9

Russo ML, Pelizza SA, Vianna MF et al (2019) Effect of endophytic entomopathogenic fungi on soybean *Glycine max* (L.) Merr. growth and yield. J King Saud Univ 31:728–736. https://doi.org/10.1016/j.jksus.2018.04.008

Ryu C-M, Kim J, Choi O et al (2006) Improvement of biological control capacity of *Paenibacillus polymyxa* E681 by seed pelleting on sesame. Biol Control 39:282–289. https://doi.org/10.1016/j.biocontrol.2006.04.014

Saha S, Rai AB, Pandey S (2011) Efficacy of seed dressing agents against damping-off disease of chilli (*Capsicum frutescens*). Indian J Agric Sci 81:92–93

Sahni S, Sarma BK, Singh DP et al (2008a) Vermicompost enhances performance of plant growth-promoting rhizobacteria in *Cicer arietinum* rhizosphere against *Sclerotium rolfsii*. Crop Prot 27: 369–376. https://doi.org/10.1016/j.cropro.2007.07.001

Sahni S, Sarma BK, Singh KP (2008b) Management of *Sclerotium rolfsii* with integration of non-conventional chemicals, vermicompost and *Pseudomonas syringae*. World J Microbiol Biotechnol 24:517–522. https://doi.org/10.1007/s11274-007-9502-8

Saidi N, Kouki S, M'Hiri F et al (2009) Characterization and selection of *Bacillus* sp. strains, effective biocontrol agents against *Fusarium oxysporum* f. sp. radicis-lycopersici, the causal agent of Fusarium crown and root rot in tomato. Ann Microbiol 59:191–198. https://doi.org/10.1007/BF03178317

Salman M, Abuamsha R (2012) Potential for integrated biological and chemical control of damping-off disease caused by *Pythium ultimum* in tomato. BioControl 57:711–718. https://doi.org/10.1007/s10526-012-9444-4

Sandhya VSKZ, Ali SZ, Grover M et al (2010) Effect of plant growth promoting *Pseudomonas* spp. on compatible solutes, antioxidant status and plant growth of maize under drought stress. Plant Growth Regul 62:21–30. https://doi.org/10.1007/s10725-010-9479-4

Sasirekha B, Shivakumar S (2012) Statistical optimization for improved indole-3-acetic acid (iaa) production by *Pseudomonas aeruginosa* and demonstration of enhanced plant growth promotion. J soil Sci plant Nutr 12:863–873. https://doi.org/10.4067/S0718-95162012005000038

Saxena J, Saini A, Kushwaha K (2016) Synergistic effect of plant growth promoting bacterium *Pseudomonas fluorescens* and phosphate solubilizing fungus Aspergillus awamori for growth enhancement of chickpea. Indian J Biochem Biophys 53:135–143. https://doi.org/10.1007/s11046-010-9307-4

Saxena MJ (2010a) Characterization of *Pseudomonas aeruginosa* RM-3 as a potential biocontrol agent. Mycopathologia 170:181–193. https://doi.org/10.1007/s11046-010-9307-4

Saxena MJ (2010b) Disease suppression and crop improvement in moong beans (*Vigna radiata*) through *Pseudomonas* and *Burkholderia* strains isolated from semi arid region of Rajasthan, India. BioControl 55:799–810. https://doi.org/10.1007/s10526-010-9292-z

Schmitt A, Koch E, Stephan D et al (2009) Evaluation of non-chemical seed treatment methods for the control of *Phoma valerianellae* on lamb's lettuce seeds. J Plant Dis Prot 116:200–207. https://doi.org/10.1007/BF03356311

Schulz TJ, Thelen KD (2008) Soybean seed inoculant and fungicidal seed treatment effects on soybean. Crop Sci 48:1975–1983

Seenivasan N, David PMM, Vivekanandan P, Samiyappan R (2012) Biological control of rice root-knot nematode, *Meloidogyne graminicola* through mixture of *Pseudomonas fluorescens* strains. Biocontrol Sci Technol 22:611–632. https://doi.org/10.1080/09583157.2012.675052

Selvakumar G, Joshi P, Nazim S et al (2009) Phosphate solubilization and growth promotion by *Pseudomonas fragi* CS11RH1 (MTCC 8984), a psychrotolerant bacterium isolated from a high altitude Himalayan rhizosphere. Biologia (Bratisl) 64:239–245. https://doi.org/10.2478/s11756-009-0041-7

Selvakumar G, Joshi P, Suyal P et al (2013) Rock phosphate solubilization by psychrotolerant *Pseudomonas* spp. and their effect on lentil growth and nutrient uptake under polyhouse conditions. Ann Microbiol 63:1353–1362. https://doi.org/10.1007/s13213-012-0594-5

Selvakumar G, Joshi P, Suyal P et al (2011) *Pseudomonas lurida* M2RH3 (MTCC 9245), a psychrotolerant bacterium from the Uttarakhand Himalayas, solubilizes phosphate and promotes wheat seedling growth. World J Microbiol Biotechnol 27:1129–1135. https://doi.org/10.1007/s11274-010-0559-4

Selvakumar G, Mohan M, Kundu S et al (2008) Cold tolerance and plant growth promotion potential of *Serratia marcescens* strain SRM (MTCC 8708) isolated from flowers of summer squash (Cucurbita pepo). Lett Appl Microbiol 46:171–175

Sen A, Singh RK, Yadaw D et al (2019) Effect of Trichoderma and hydrogel on growth, yield and yield attributes of direct seeded rice (*Oryza sativa*) under rainfed condition. Indian J Agric Sci 89:333–338

Shanmugam V, Kanoujia N (2011) Biological management of vascular wilt of tomato caused by *Fusarium oxysporum* f. sp. lycospersici by plant growth-promoting rhizobacterial mixture. Biol Control 57:85–93. https://doi.org/10.1016/j.biocontrol.2011.02.001

Shanmugam V, Senthil N, Raguchander T et al (2002) Interaction of *Pseudomonas fluorescens* with Rhizobium for their effect on the management of peanut root rot. Phytoparasitica 30:169–176. https://doi.org/10.1007/BF02979699

Sharma A, Wray V, Johri BN (2007) Rhizosphere *Pseudomonas* sp. strains reduce occurrence of pre-and post-emergence damping-off in chile and tomato in Central Himalayan region. Arch Microbiol 187:321–335. https://doi.org/10.1007/s00203-006-0197-2

Sharma V, Sharma S, Sharma S, Kumar V (2019) Synergistic effect of bio-inoculants on yield, nodulation and nutrient uptake of chickpea (*Cicer arietinum* L) under rainfed conditions. J Plant Nutr 42:374–383. https://doi.org/10.1080/01904167.2018.1555850

Shawky BT (1990) Effect of azotobacters and azospirilla on germination of seeds of some agricultural crops. Zentralblatt fur Mikrobiol 145: 209–217

Shcherbakova EN, Shcherbakov AV, Andronov EE et al (2017) Combined pre-seed treatment with microbial inoculants and Mo nanoparticles changes composition of root exudates and rhizosphere microbiome structure of chickpea (*Cicer arietinum* L.) plants. Symbiosis 73:57–69. https://doi.org/10.1007/s13199-016-0472-1

Shifa H, Gopalakrishnan C, Velazhahan R (2018) Management of late leaf spot (*Phaeoisariopsis personata*) and root rot (*Macrophomina phaseolina*) diseases of groundnut (*Arachis hypogaea* L.) with plant growth-promoting rhizobacteria, systemic acquired resistance inducers and plant extracts. Phytoparasitica 46:19–30. https://doi.org/10.1007/s12600-018-0644-z

Shishido M, Chanway CP (2000) Colonization and growth promotion of outplanted spruce seedlings pre-inoculated with plant growth-promoting rhizobacteria in the greenhouse. Can J For Res 30:845–854

Silveira EB, Gomes A, Mariano RL, Silva Neto EB (2004) Bacterization of seeds and development of cucumber seedlings. Hortic Bras 22: 217–221
Singh GR, Choudhary KK, Chaure NK, Pandya KS (1996) Effect of seed bacterization and nitrogen level on soil properties yield parameters, yield and economics of sunflower (*Helianthus annuus*). Indian J Agric Sci 66:250–252
Singh NK, Chaudhary FK, Patel DB (2013a) Effectiveness of Azotobacter bio-inoculant for wheat grown under dryland condition. J Environ Biol 34:5
Singh P, Kumar V, Agrawal S (2014) Evaluation of phytase producing bacteria for their plant growth promoting activities. Int J Microbiol 2014:3. https://doi.org/10.1155/2014/426483
Singh RB, Singh HK, Parmar A (2013b) Integrated management of alternaria blight in linseed. Proc Natl Acad Sci India Sect B Biol Sci 83:465–469. https://doi.org/10.1007/s40011-012-0152-8
Souto GI, Correa OS, Montecchia MS et al (2004) Genetic and functional characterization of a *Bacillus* sp. strain excreting surfactin and antifungal metabolites partially identified as iturin-like compounds. J Appl Microbiol 97:1247–1256. https://doi.org/10.1111/j.1365-2672.2004.02408.x
Stauffer CS, Haefele DM, Hendrick CA et al (1991) A quantitative disease bioassay for selection of fluorescent pseudomonads which suppress preemergence damping-off of hybrid field corn caused by pythium spp. Biol Control 1:210–217
Stef R, Grozea I, Puia C et al (2014) The effect of seed treatment on the main pathogens present in wheat agroecosystems. Commun Agric Appl Biol Sci 79:473–479
Strejckova M, Bohata A, Olsan P et al (2018) Enhancement of the yield of crops by plasma and using of entomopathogenic and mycoparasitic fungi: from laboratory to large-field experiments. J Biomater Tissue Eng 8:829–836
Subramanian P, Mageswari A, Kim K et al (2015) Psychrotolerant endophytic *Pseudomonas* sp. strains OB155 and OS261 induced chilling resistance in tomato plants (*Solanum lycopersicum* Mill.) by activation of their antioxidant capacity. Mol Plant-Microbe Interact 28: 1073–1081. https://doi.org/10.1094/MPMI-01-15-0021-R
Sun T, Shen Z, Shaukat M et al (2020) Endophytic isolates of *Cordyceps fumosorosea* to enhance the growth of *Solanum melongena* and reduce the survival of whitefly (*Bemisia tabaci*). Insects 11:2. https://doi.org/10.3390/insects11020078
Suproniene S, Semaskiene R, Juodeikiene G et al (2015) Seed treatment with lactic acid bacteria against seed-borne pathogens of spring wheat. Biocontrol Sci Technol 25:144–154. https://doi.org/10.1080/09583157.2014.964661
Swkedrzyńska D (2000) Effect of inoculation with *Azospirillum brasilense* on development and yielding of winter wheat and oat under different cultivation conditions. Pol J Env 9:423–428
Sytnikov D, Vorobey N, Kots S (2009) Physiological reaction of legume plants to inoculation with algal-rhizobial associations. Acta Agron Hungarica 57:239–244. https://doi.org/10.1556/AAgr.57.2009.2.15
Szopińska D, Jensen B, Knudsen IMB et al (2010) Non-chemical methods for controlling seedborne fungi in carrot with special reference to *Alternaria radicina*. J Plant Prot Res 50:184–192 doi: http://www.plantprotection.pl/Non-chemical-methods-for-controlling-seedborne-fungi-in-carrot-with-special-reference,91525,0,2.html
Tavanti TR, Tavanti RF, Galindo FS et al (2020) Yield and quality of soybean seeds inoculated with Bacillus subtilis strains. Rev Bras Eng Agricola e Ambient 24:65–71
Teixeira GA, Alves E, Amaral DC et al (2013) Essential oils on the control of stem and ear rot in maize. Ciência Rural 43:1945–1951
Tosi L, Zazzerini A (1994) Evaluation of some fungi and bacteria for potential control of safflower rust. J Phytopathol 142:131–140
Tripathi M, Johri BN, Sharma A (2006) Plant growth–promoting *Pseudomonas* sp. strains reduce nat occur anthracnose soybean (*Glycine max* L). Cent Himal Reg 52:390–394. https://doi.org/10.1007/s00284-005-0297-2
Tsahouridou PC, Thanassoulopoulos CC (2002) Proliferation of *Trichoderma koningii* in the tomato rhizosphere and the suppression of damping-off by *Sclerotium rolfsii*. Soil Biol Biochem 34:767–776. https://doi.org/10.1016/S0038-0717(02)00006-8
Tsavkelova EA, Egorova MA, Leontieva MR et al (2016) Dendrobium nobile Lindl. seed germination in co-cultures with diverse associated bacteria. Plant Growth Regul 80:79–91. https://doi.org/10.1007/s10725-016-0155-1
Ugoji EO, Laing MD (2008) Rhizotron studies on *Zea mays* L. to evaluate biocontrol activity of *Bacillus subtilis*. World J Microbiol Biotechnol 24:269–274. https://doi.org/10.1007/s11274-007-9466-8
Vakili NG (1992) Biological seed treatment of corn with mycopathogenic fungi. J Phytopathol 134:313–323. https://doi.org/10.1111/j.1439-0434.1992.tb01239.x
Van Bruggen AHC, Francis IM, Jochimsen KN (2014) Non-pathogenic rhizosphere bacteria belonging to the genera *R hizorhapis* and *S phingobium* provide specific control of lettuce corky root disease caused by species of the same bacterial genera. Plant Pathol 63: 1384–1394
Vancura V, Macura J, Fischer O, Vondrácek J (1959) The relation of Azotobacter to the root system of barley. Folia Microbiol (Praha) 4:119–129
van der Wolf JM, Birnbaum Y, der Zouwen PS, Groot SPC (2008) Disinfection of vegetable seed by treatment with essential oils, organic acids and plant extracts. Seed Sci Technol 36:76–88
van Dijk K, Nelson EB (1998) Inactivation of seed exudate stimulants of *Pythium ultimum* sporangium germination by biocontrol strains of *Enterobacter cloacae* and other seed-associated bacteria. Soil Biol Biochem 30:183–192. https://doi.org/10.1016/S0038-0717(97)00106-5
Vanitha SC, Niranjana SR, Mortensen CN, Umesha S (2009) Bacterial wilt of tomato in Karnataka and its management by *Pseudomonas fluorescens*. Biocontrol 54:685–695. https://doi.org/10.1007/s10526-009-9217-x
Vankosky MA, Cárcamo HA, McKenzie RH, Dosdall LM (2011) Integrated management of Sitona lineatus with nitrogen fertilizer, Rhizobium, and thiamethoxam insecticide. Agron J 103:565–572. https://doi.org/10.2134/agronj2010.0314
Varma S, Mathur RS (1990) The effects of microbial inoculation on the yield of wheat when grown in straw-amended soil. Biol wastes 33:9–16
Vidhyasekaran P, Kamala N, Ramanathan A, et al (2001) Induction of systemic resistance by *Pseudomonas fluorescens* Pf1 against *Xanthomonas oryzae* pv. *oryzae* rice leaves 29:155–166. https://doi.org/10.1007/BF02983959
Vidhyasekaran P, Muthamilan M (1995) Development of formulations of *Pseudomonas fluorescens* for control of chickpea wilt. Plant Dis 79:782–786
Vidhyasekaran P, Muthamilan M (1999) Evaluation of a powder formulation of *Pseudomonas fluorescens* Pf1 for control of rice sheath blight. Biocontrol Sci Technol 9:67–74
Vidhyasekaran P, Rabindran R, Muthamilan M et al (1997) Development of a powder formulation of *Pseudomonas fluorescens* for control of rice blast. Plant Pathol 46:291–297
Vogel GF, Fey R (2019) *Azospirillum brasilense* interaction effects with captan and thiodicarb on the initial growth of corn plants. J Neotrop Agric 6:53–59
Vogel GF, Martinkoski L, Jadoski SO, Fey R (2015) Efeitos na combinaçao de *Azospirillum brasilense* com fungicidas no desenvolvimento de trigo. Brazilian J Appl Technol Agric Sci Bras Tecnol Apl nas Ciências Agrárias 8:73–80
Vraný J, Vancura V, Stanek M (1981) Control of microorganisms in the rhizosphere of wheat by inoculation of seeds with

Pseudomonas putida and by foliar application of urea. Folia Microbiol (Praha) 26:45–51

Vyas P, Joshi R, Sharma KC et al (2010) Cold-adapted and rhizosphere-competent strain of *Rahnella* sp. with broad-spectrum plant growth-promotion potential. J Microbiol Biotechnol 20:1724–1734

Wakelin SA, Anstis ST, Warren RA, Ryder MH (2006) The role of pathogen suppression on the growth promotion of wheat by *Penicillium radicum*. Australas Plant Pathol 35:253–258. https://doi.org/10.1071/AP06008

Wharton PS, Kirk WW (2014) Evaluation of biological seed treatments in combination with management practices for the control of Fusarium dry rot of potato. Biol Control 73:23–30. https://doi.org/10.1016/j.biocontrol.2014.03.003

Wilson RG, Young BG, Matthews JL et al (2011) Benchmark study on glyphosate-resistant cropping systems in the United States. Part 4: weed management practices and effects on weed populations and soil seedbanks. Pest Manag Sci 67:771–780

Windels CE, Kommedahl T (1982) Pea cultivar effect on seed treatment with *Penicillium oxalicum* in the field [*Pisum sativum*, biological control antagonist, fungus diseases]. Phytopathology 72:541–543

Wu WS, Wu HC, Li YL (2007) Potential of *Bacillus amyloliquefaciens* for control of *Alternaria cosmosa* and A. patula of *Cosmos sulfurous* (Yellow Cosmos) and Tagetes patula (French Marigold). J Phytopathol 155:670–675

Xue AG (2000) Effect of seed-borne *Mycosphaerella pinodes* and seed treatments on emergence, foot rot severity, and yield of field pea. Can J Plant Pathol 22:248–253

Xue AG, Cober E, Morrison MJ et al (2007) Effect of seed treatments on emergence, yield, and root rot severity of soybean under *Rhizoctonia solani* inoculated field conditions in Ontario. Can J plant Sci 87:167–174. https://doi.org/10.4141/P05-192

Xue AG, Guo W, Chen Y et al (2017) Effect of seed treatment with novel strains of *Trichoderma* spp. on establishment and yield of spring wheat. Crop Prot 96:97–102. https://doi.org/10.1016/j.cropro.2017.02.003

Yadav AK, Yandigeri MS, Vardhan S et al (2014) *Streptomyces* sp. S160: a potential antagonist against chickpea charcoal root rot caused by *Macrophomina phaseolina* (Tassi) Goid. Ann Microbiol 64:1113–1122. https://doi.org/10.1007/s13213-013-0750-6

Yadav MS, Godika S, Yadava DK et al (2019) Prioritizing components of package of integrated pest management in Indian mustard (*Brassica juncea*) in India for better economic benefit. Crop Prot 120:21–29. https://doi.org/10.1016/j.cropro.2019.02.008

Yildirim E, Taylor AG, Spittler TD (2006) Ameliorative effects of biological treatments on growth of squash plants under salt stress. Sci Hortic (Amsterdam) 111:1–6. https://doi.org/10.1016/j.scienta.2006.08.003

Yogeshwar D, Gade RM, Shitole AV (2017) Evaluation of antifungal activities of extracts of *Aegle marmelos, Syzygium cumini* and *Pongamia pinnata* against *Pythium debaryanum*. Indian J Pharm Sci 79:377–384

Yolageldi L, Turhan G (2005) Effect of biological seed treatment with *Cylindrocarpon olidum* var. *olidum* on control of common bunt (*Tilletia laevis*) of wheat. Phytoparasitica 33:327–333. https://doi.org/10.1007/BF02981298

Yuan Y, Feng H, Wang L et al (2017) Potential of endophytic fungi isolated from cotton roots for biological control against verticillium wilt disease. PLoS One 12:1. https://doi.org/10.1371/journal.pone.0170557

Zamoum M, Goudjal Y, Sabaou N et al (2017) Development of formulations based on *Streptomyces rochei* strain PTL2 spores for biocontrol of *Rhizoctonia solani* damping-off of tomato seedlings. Biocontrol Sci Technol 27:723–738. https://doi.org/10.1080/09583157.2017.1334257

Zandona RR, Pazdiora PC, Pazini JB et al (2019) Chemical and biological seed treatment and their effect on soybean development and yield. Rev. Caatinga 32:559–565

Zhang S, Xu B, Gan Y (2019) Seed treatment with *Trichoderma longibrachiatum* T6 promotes wheat seedling growth under NaCl stress through activating the enzymatic and nonenzymatic antioxidant defense systems. Int J Mol Sci 20:15. https://doi.org/10.3390/ijms20153729

Zhao J, Liu D, Wang Y et al (2020) Evaluation of *Bacillus aryabhattai* Sneb517 for control of *Heterodera glycines* in soybean. Biol Control 142. https://doi.org/10.1016/j.biocontrol.2019.104147

Zhou L, Zhang L, He Y et al (2014) Isolation and characterization of bacterial isolates for biological control of clubroot on Chinese cabbage. Eur J plant Pathol 140:159–168. https://doi.org/10.1007/s10658-014-0451-4

Zilli JÉ, Campo RJ, Hungria M (2010) Eficácia da inoculaçao de Bradyrhizobium em pré-semeadura da soja. Pesqui Agropecuária Bras 45:335–337