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Endophytic bacteria improve mesorhizobial nodulation, plant growth and yield in chickpea (*Cicer arietinum*)

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ABSTRACT

The aim of our study was to determine the symbiotic effectiveness of *Mesorhizobium ciceri* and plant growth promotion of endophytic bacteria in field-grown chickpea during 2016–17 and 2017–18. Co-inoculation of *M. ciceri* along with various endophytes has significantly improved soil dehydrogenase activity in chickpea rhizosphere. The combined inoculation of *M. ciceri* with nodule endophytes, viz. *Bacillus cereus* (25.7–51.9%) and *Bacillus aerophilus* (18.6–27.8%) showed higher nodule weight than uninoculated control which is at par with inoculation of *M. ciceri* with root endophyte (*Pseudomonas flourescens*). Co-inoculation of *M. ciceri* + *B. aerophilus* increased chickpea growth (13.7–21.5%) at 50% flowering stage and grain yield (15.6–18.2%) at harvest stage which is at par with the treatment with *P. flourescens* (17.5–20.1%). A positive correlation was observed between nodule dry weight with growth and yield of chickpea in the second year. Co-inoculation of endophytic bacteria has improved the symbiotic efficiency, growth and productivity of chickpea through synergistic interaction with *Mesorhizobium*.

Keywords: Chickpea, Endophytic bacteria, *Mesorhizobium*, Nodulation, Productivity

In India, chickpea cultivation is generally practised under rainfed conditions. Chickpea forms symbiotic association with *Mesorhizobium* species which can convert atmospheric nitrogen into ammonia through symbiotic nitrogen fixation (Nour *et al.* 1994). The amount of nitrogen fixed in Chickpea –*Mesorhizobium* symbiosis varies from of 3-121 N/kg/ha (Peoples *et al.* 1995). Growing chickpea in crop rotation benefits the succeeding crop by enhanced N supply from the soil. Plant growth promoting rhizobacteria (PGPR) and endophytic bacteria influenced rhizobial symbiosis positively (Swarnalakshmi *et al.* 2019, Swarnalakshmi *et al.* 2020). The combined inoculation of rhizobia and rhizobacteria is more effective as the latter can modify nodule formation and nitrogen fixation in grain legumes (Verma *et al.* 2013). The endophytic microorganisms induced nodulation and growth in chickpea and exhibit more pronounced plant growth-promoting effects than rhizobacteria (Ahmad *et al.* 2019). A large number of non-rhizobial endophytic bacterial genera, viz. *Agrobacterium, Pseudomonas, Enterobacter, Pantoea, Bacillus* and *Paenibacillus* are more frequently isolated from root, shoot and nodule tissues of different legumes (Kan *et al.* 2007, Li *et al.* 2008, Ahmad *et al.* 2019). The presence of nodule associated endophytes, viz. *Agrobacterium, Bacillus, Curtobacterium, Enterobacter, Erwinia, Herbaspirillum, Mycobacterium, Paenibacillus, Pseudomonas, Phyllobacterium, Ochrobactrum, Sphingomonas, Rhizobium, Ensifer, Mesorhizobium, Burkholderia, Phyllobacterium* and *Devosia* are reported in leguminous plants (Dudeja *et al.* 2012). They can enter into the plant tissues along with the nodule bacteria and capable of co-habiting with *Rhizobium* in root nodules. These endophytic bacteria are reported to enhance plant growth promotion through phosphate solubilisation, nitrogen assimilation, iron chelation and pathogen suppression (Rosenblueth and Martínez-Romero 2006, Liu *et al.* 2009).

As chickpea is grown under marginal lands, emphasis has been given on seed inoculation with *Mesorhizobium* and other beneficial microorganisms to provide the plant nutrition. Interactive effects of *Mesorhizobium* and rhizobacteria have been demonstrated. However, reports on the synergistic effect of endophytic bacteria with *Mesorhizobium* on growth and productivity of chickpea under field conditions are scanty. The present investigation was carried out to evaluate the comparative performance of various endophytic bacterial strains along with *Mesorhizobium* on nodulation, plant growth and productivity of chickpea under field conditions.

MATERIALS AND METHODS

Field experiment was conducted at ICAR-Indian Agricultural Research Institute, New Delhi, India (28º40'

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N latitude and 77º12' E longitude, 229 m amsl) during *rabi* (November–April) season of two consecutive years (2016–17 and 2017–18). The climate of an experimental unit is semi-arid with an average annual rainfall of approximately 650 mm, 80% of which is received through south-west monsoon during July to September and the rest is received during the 'Western Disturbances' in the months of December to February. The chickpea crop was sown with the residual moisture during *rabi*. The mean daily maximum temperature during the crop growth period varied from 25–34ºC, whereas December–January are the coldest months with the mean daily minimum temperature ranging from 5–8ºC.

The experiment was laid out in randomized block design and replicated three times with the plot size of 10 m^2. The soil samples (0-15 cm depth) were taken at the beginning of the experiment. The soil was sandy–loam in texture, with a *p*H of 7.34, organic carbon, 0.6% (Walkley and Black 1934) and electrical conductivity (EC) was 0.23 dS/m. The alkaline $KMnO_4$ oxidizable–N was 213.3 kg/ha (Subbiah and Asija 1956) and 0.5 M $NaHCO_3$ extractable P was 18.9 kg/ha (Olsen *et al.* 1954). The experiment comprised 10 treatments. The treatment without inoculants served as a control (T_1). A single inoculation of *Mesorhizobium ciceri*- CH 1233 (T_2) was added to compare the co-inoculation effect. The co-inoculation of *M. ciceri* with different endophytic bacteria strains (T_5 to T_{10}) were compared with reference check (T_3: *M. ciceri* + CNE 1) and combined inoculation of *M.ciceri* + PGPR (T_4: *M. ciceri +Pseudomonas argentinensis*). All endophytes were isolated from chickpea nodules (NE) except the *Pseudomonas flourescens* (T_5) which was isolated from chickpea roots (RE).

The details of treatments are; T_1: Uninoculated control; T_2: *Mesorhizobium ciceri* CH 1233; T_3: *M. ciceri* + CNE 1 (ref. check); T_4: *M. ciceri +Pseudomonas argentinensis* (PGPR); T_5: *M. ciceri +Pseudomonas flourescens* (RE); T_6: *M. ciceri +Pseudomonas aeruoginosa* (NE); T_7: *M. ciceri+ Bacillus cereus* (NE); T_8: *M. ciceri+ Bacillus aerophilus* (NE); T_9: *M. cicero + Pseudomonas flourescens* (NE); T_{10}: *M. ciceri+ Enterobacter* sp. (NE).

Chickpea seeds (cv. BG 372) were inoculated using carrier (vermiculite) based endophytic microbial inoculants containing 10^9 CFU (colony forming unit)/g using carboxy methyl cellulose (1%) as a sticker. The inoculated seeds were sown in the field during the first week of November 2017 and 2018. Each plot had 10 rows with 30 cm × 10 cm spacing. Fertilizer was applied at 100 kg DAP as a basal dose. No irrigation was given during the crop growth period. Plant and rhizosphere soil samples were collected at 50% flowering stage and analysed for nodulation potential, plant growth and dehydrogenase activity. The biomass and grain yield were recorded at the harvesting stage.

Dehydrogenase activity: Dehydrogenase activity of the soil was determined using 2,3,5-Triphenyl tetrazolium chloride (TTC) test given by Casida (1977). About 5g soil was taken in test tubes, and 1 ml of 3% TTC was added. The tubes were sealed airtight and incubated at room temperature for 24 hr in the dark. After the incubation period, 10 ml methanol was added, and the content was filtered using Whatman No.1 filter paper. The red colour developed due to TPF (Triphenyl formazan) formation was measured at 485nm.

Nodulation potential: The chickpea plants were uprooted with an intact root system and washed with running tap water to remove the adhering soil particles. The root nodules were detached carefully and the nodule number per plant was recorded. These nodules were then dried at 70° C for two days in a hot air oven and nodule dry weight (mg/plant) was weighed.

Plant growth and yield: The plant growth was determined by separating both the root and shoot of the plant samples. The samples were dried in the hot air oven at 70°C till the constant weight is achieved. At the harvest stage, the biomass and grain yield per plot was recorded.

Statistical analysis: The data recorded on various parameters were subjected to analysis of variance (ANOVA) and post hoc mean separation was performed by the Duncan's Multiple Range Test (DMRT). The mean values were separated according to LSD test at $P<0.05$. All statistical analysis was performed using SPSS (version 18.0) software.

RESULTS AND DISCUSSION

Rhizosphere soil dehydrogenase activity: There was a significant effect of microbial inoculation on rhizosphere soil dehydrogenase activity (Table 1). The uninoculated control showed the lowest dehydrogenase activity whereas the greatest change in the dehydrogenase activity was observed with combined inoculation of *M. ciceri* with endophytic bacterial strain during both seasons. In 2016-17, comparison between uninoculated control (T_1) with T_8 (*M. ciceri* + *B. aerophilus*) showed an increase of 147% followed by T_5 (*M. ciceri* + *P. flourescens*) and T_9 (*M. ciceri*+ *P. flourescens*) which also showed a concurrent increase in nodule dry weight. In the second year, the reference check (T_3) showed an increase of 24% over uninoculated control followed by T_6 (*M. ciceri* + *P. aeruoginosa*). Gopalakrishnan *et al.* (2015) found that inoculation of *Streptomyces* sp. in the soil is found to increase dehydrogenase activity by 21%. Measurement of dehydrogenase activity reflects the changes in the microbial activity in the rhizosphere soil following the inoculation. This enzyme plays a key role in soil organic matter due to transfer of hydrogen from organic substrates to inorganic acceptors which are involved in a reductive process of biosynthesis and thus are an important part of enzyme systems of living microorganisms (Wolinska and Stepniewska 2012). A positive correlation between dehydrogenase activity and nodule dry weight (0.36 in 2016-17 and 0.66 in 2017-18) was observed during both the seasons indicates that inoculation can significantly influence the rhizosphere microbial activity in chickpea, which in turn can improve the nodulation synergistically.

Nodulation potential: Root nodules are the most significant part of legumes–rhizobial symbiosis. Inoculation of legume crop with root nodulating rhizobia has been

Table 1 Synergistic effect of *Mesorhizobium ciceri* and endophytic bacteria on nodulation and rhizosphere soil dehydrogenase activity at 50% flowering

Treatment	*Rabi* 2016-17			*Rabi* 2017-18		
	Nodules/ plant	Nodule dry weight (mg/plant)	Dehydrogenase activity (µg TPF/day/100 g soil)	Nodules/ plant	Nodule dry weight (mg/plant)	Dehydrogenase activity (µg TPF/day/100 g soil)
T_1	6.3	107.67^{abc}	121.56^{f}	9.00	90.00^{c}	100.54^{d}
T_2	13.33	109.33^{abc}	124.54^{f}	11.67	110.00^{b}	109.76^{bcde}
T_3	11.00	102.00^{bc}	159.80^{c}	9.33	113.33^{b}	124.71^{a}
T_4	13.33	47.67^{e}	150.82^{cd}	9.00	113.33^{b}	107.16^{cde}
T_5	14.00	122.33^{ab}	202.27^{b}	11.00	140.00^{a}	116.29^{abc}
T_6	14.00	66.67^{de}	142.84^{de}	13.33	140.00^{a}	117.85^{ab}
T_7	13.00	135.33^{a}	132.58^{ef}	13.33	136.67^{a}	115.15^{abc}
T_8	11.33	127.67^{ab}	300.42^{a}	10.00	115.00^{b}	104.73^{de}
T_9	10.33	114.00^{abc}	187.54^{b}	11.33	120.00^{ab}	111.72^{bcd}
T_{10}	13.00	90.00^{cd}	126.10^{f}	7.33	120.00^{ab}	115.75^{abc}

Letters in superscripts indicate mean separation by Duncan's multiple range test ($P \leq 0.05$).

recommended for improving plant growth and productivity. The nodule number per plant was non-significant with mesorhizobial inoculation with endophytic bacteria in both the seasons of *rabi* 2016-17 and 2017-18 (Table 1). Improved performance with *Mesorhizobium* inoculation in the second-year highlights that the introduced strain is effective and outcompete the indigenous population. The highest nodule dry weight was produced from T_7 (*M. ciceri* + *Bacillus cereus*) with an increase of 25.69% over uninoculated control followed by T_8 and T_5 during 2016-17 while T_5 (*M. ciceri* + *P. flourescens*) showed 55.56% increase over T_1 (uninoculated control) during subsequent year which is at par with treatment involving nodule endophytes, viz. T_6 (*M. ciceri* + *P. aeruoginosa*) and T_7 (*M. ciceri* + *B. cereus*) followed by T_8: (*M. ciceri* + *Bacillus aerophilus*). In soybean, the inoculation of *Rhizobium* sp., *Pseudomonas* sp., *Streptomyces* sp. and *Bradyrhizobium* sp. have increased the nodule formation (Soe *et al.* 2012). The endophytic bacteria inoculated along with *Mesorhizobium* sp. have also shown an increase in plant nodulation in chickpea (Saini *et al.* 2015). In the current study, a significant change in nodule dry weight with combined inoculation of *Mesorhizobium* with various endophytic *Pseudomonas* sp. And *Bacillus* sp. indicates that the beneficial bacterial strains can influence the mesorhizobial symbiosis synergistically. These *Pseudomonas* sp., *Bacillus* sp. and *Mesorhizobium ciceri* are also reported as phosphate solubilizers (Ahmad *et al.* 2008). Field trials also showed the synergistic effects of *Mesorhizobium* and phosphate solubilizing microorganism on improving nodulation (Valverde *et al.* 2006, Wani *et al.* 2007, Verma *et al.* 2013). As P is important for N fixation, inoculation of endophytic *Pseudomonas* sp., *Bacillus* sp. can positively influence *Mesorhizobium* symbiosis.

Plant growth: Seed inoculation with *M. ciceri* along with various endophytic bacteria has significantly improved chickpea plant growth at 50% flowering (Table 2). In our study, uninoculated control showed the lowest shoot and root weight in both the seasons. A comparative analysis of the T_1 (uninoculated control) and T_8 (*M.ciceri* + *B. aerophilus*) showed an increase of 15.6% shoot growth in 2016-17, which is at par with T_3 and T_5 which comprise endophytic strains. A similar trend was observed with respect to root growth where T_8 (*M. ciceri* + *B. aerophilus*) showed 19% increased root growth over T_1(uninoculated control) during 2016-17. In the second year, T_5 (*M.ciceri* + *Pseudomonas flourescens*) showed 29.9% increased shoot growth over uninoculated control followed by T_8, whereas with respect to root growth T_4 (*M. ciceri* + *P. argentinensis* accounted 43% increase over uninoculated control followed by $T_{2,}$ T_5, T_6, T_8, T_9 and T_{10}. In the first year, nodule number/plant was positively correlated with shoot growth (0.67) however in the second year a positive correlation between nodule dry weight with shoot (0.7) and root (0.67) growth was observed. Our results were in conformity with Saini *et al.* (2015) who reported that co-inoculation of endophytic bacteria along with *Mesorhizobium* sp. could increase root and shoot dry weight of chickpea.The inoculation of *Rhizobium* along with *Azotobacter* sp*.*, *Bacillus* sp*.*, *Pseudomonas* sp*.*, *Piriformospora indica* and *Trichoderma* sp. stimulatethe plant growth and nodulation in field-grown legumes (Korir *et al.* 2017, Swarnalakshmi *et al.* 2017). The increased chickpea growth by combined inoculation of *Mesorhizobium* sp. and *Pseudomonas* sp. may be due to improved N and P uptake (Verma *et al.* 2013). These bacteria also promote plant growth by production of phytohormones and vitamins in the rhizosphere (Swarnalakshmi *et al.* 2020). Besides that, the endophytic bacteria can induce systemic resistance in plants by inducing phenol production and protect from multiple pathogens, which directly helps in improving the overall plant growth (Rangeswaran *et al.* 2008).

Table 2 Synergistic effect of *Mesorhizobium ciceri* and endophytic bacteria on plant growth and yield of chickpea

Treatment	*Rabi* 2016-17				*Rabi* 2017-18			
	Shoot weight (g/plant)	Root weight (mg/plant)	Biomass (kg/ha)	Yield (kg/ha)	Shoot weight (g/plant)	Root weight (mg/plant)	Biomass (kg/ha)	Yield (kg/ha)
T_1	5.44^{c}	0.47^{d}	7733.3^{bc}	2666.7^{c}	2.11^{e}	0.23^{c}	5142.9^{b}	1215.2^{c}
T_2	5.93^{b}	0.53^{abc}	7700.0^{c}	2766.7^{bc}	2.38^{d}	0.29^{ab}	5866.7^{a}	1356.2^{bc}
T_3	6.27^{a}	0.52^{abcd}	8333.3^{abc}	2866.7^{abc}	2.50^{bcd}	0.29^{ab}	6400.0^{a}	1432.4^{a}
T_4	6.00^{ab}	0.55^{b}	8466.7^{ab}	2800.0^{abc}	2.64^{abc}	0.33^{a}	6438.1^{a}	1367.6^{bc}
T_5	6.26^{a}	0.51^{abcd}	9033.3^{a}	3133.3^{a}	2.74^{a}	0.32^{ab}	6400.0^{a}	1459.1^{a}
T_6	6.20^{ab}	0.49^{cd}	8266.7^{abc}	2700.0^{c}	2.47^{cd}	0.29^{ab}	6247.6^{c}	1436.2^{a}
T_7	5.92^{b}	0.49^{cd}	8566.7^{a}	3066.7^{ab}	2.59^{abc}	0.27^{bc}	6095.2^{a}	1386.7^{a}
T_8	6.29^{a}	0.56^{a}	8733.3^{a}	3083.3^{ab}	2.67^{ab}	0.31^{ab}	6323.8^{a}	1436.9^{a}
T_9	5.87^{b}	0.50^{bcd}	8400.0^{abc}	2833.3^{abc}	2.46^{cd}	0.30^{ab}	6323.8^{a}	1405.7^{a}
T_{10}	6.07^{ab}	0.49^{cd}	8666.7^{a}	2700.0^{c}	2.48^{cd}	0.29^{ab}	6247.6^{a}	1405.7^{a}

Letters in superscripts indicate mean separation by Duncan's multiple range test ($P \leq 0.05$).

Biomass and grain yield: Inoculation effect of *M.ciceri* and endophytic bacteria significantly improved biomass and grain yield of chickpea over uninoculated control (T_1) during both seasons (Table 2). Dual inoculation has shown greater yield than the *Mesorhizobium* inoculation alone. Higher biomass was observed with T_5 (*M. ciceri +P. flourescens*) with 9033.3 kg/ha biomass and with an increase of 16.8% with comparison to the uninoculated control which is at par with T_7, T_8 and T_{10} treatments comprising nodule endophytes. In 2017-18, biomass ranged from 5142-6438 kg/ha with the highest content recorded from *M. ciceri* with *PGPR* (T_4) with an increase of 25.2% as compared to the uninoculated control which was at par with T_3, T_5, T_7, T_8, T_9 and T_{10} treatments comprising endophytes. Unlike PGPRs, endophytes have an advantage as they can colonize internal plant tissues and get better protection from environmental stresses and microbial competitions. The plant growth promoting substances such as indole-3-acetic acid, gibberellins and cytokinins produced by the endophytic bacteria can also improve the plant growth at different stages (Ali *et al.* 2017, Swarnalakshmi *et al.* 2019).

The highest grain yield was recorded from T_5 (*M. ciceri +P. flourescens*) with an increase of 17.5% as compared to the uninoculated control followed by T_7 (15%) and T_8 (15.62%) in 2016-17. The similar trend was observed during second year with T_5 leading to 20.1% increase over control (T_1) which is at par with T_3 (17.9%), T_6 (18.2%), T_7 (14.1%),T_8 (18.2%), T_9 (15.7%) and T_{10} (15.7%). Overall, T_5 and T_8 showed consistent performance over the years in improving nodulation, growth and productivity of chickpea. In 2016-17, the improved shoot growth with microbial inoculation was significantly correlated with biomass and grain yield. In second year (2017-18), nodule dry weight was positively correlated with shoot growth (0.7) and yield (0.76) ($P<0.05$). The synergistic effect of *Mesorhizobium* with *Bacillus* or *Pseudomonas* on chickpea growth, yield and grain protein was reported by Wani *et al.* (2007). In accordance with our findings, an increase of 12.5% in yield was recorded due to microbial co-inoculation of *Bacillus megaterium* and *Rhizobium* sp. in chickpea was observed by Aparna *et al.* (2014).Our previous field trials highlight the positive effects of application phosphatic fertilizer along with inoculation of *Mesorhizobium*, *Pseudomonas* sp., *Piriformospra indica* and *Trichoderma* sp. which together accounted 35% increase in grain yield over uninoculated control due to improved nitrogen and phosphorus nutrition (Swarnalakshmi *et al.* 2017). In the present study, it is evident that among the treatment involving various endophytes, *M. ciceri + P. flourescens* and *M. ciceri + B.cereus* are significantly increased nodule biomass, growth and yield of chickpea. This may be due to the enhanced supply of N through symbiotic nitrogen fixation by *Mesorhizobium* and plant growth-promoting potential of *Pseudomonas strain*. Our results indicate that inoculation of *Mesorhizobium* and endophytic bacteria can augment chickpea production over and above the application of the recommended dose of chemical fertilizer.

Our findings have showed clear evidence that inoculation of endophytic bacteria and *Mesorhizobium ciceri* can significantly improve the nodulation potential, plant growth and rhizosphere dehydrogenase activity. The combined inoculation of *M. ciceri* with *Bacillus* sp. and *Pseudomonas flourescens* enhanced the nodule biomass. The co-inoculation effect of *Mesorhizobium* with endophytic bacteria was more pronounced on plant growth at flowering stage, which was also reflected in improved seed yield at harvest stage. The nodule biomass, plant growth and yield attributes were positively correlated. Our study signifies that dual-inoculation of *M. ciceri* with endophytic bacteria has significant potential to improve nodulation and overall growth and productivity of chickpea crop in a synergistic manner.

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REFERENCES

Ahmad F, Ahmad I and Khan M S. 2008. Screening of free-living rhizospheric bacteria for their multiple plant growth promoting activities. *Microbiological Research* **163**(2): 173–81.

Ahmad M, Naseer, I, Hussain A, Mumtaz M Z, Mustafa A, Hilger T H, Zahir Z A and Minggang X. 2019. Appraising endophyte–plant symbiosis for improved growth, nodulation, nitrogen fixation and abiotic stress tolerance: An experimental investigation with chickpea (*Cicer arietinum* L.). *Agronomy* **9**(10): 621.

Ali S, Charles T C and Glick B R. 2017. Endophytic phytohormones and their role in plant growth promotion. *Functional Improvement of the Plant Microbiome*, pp 89–105. Doty S L (Ed), Springer International Publishing.

Aparna K, Rao D L N and Manna M C. 2014. Microbial inoculation of chickpea (*Cicer arietinum* L.) enhances rhizosphere effects on soil biological quality. *Agrochimica* **58**(2): 114–25.

Casida L E. 1977. Microbial metabolic activity in soil as measured by dehydrogenase determinations. *Applied Environmental Microbiology* **34**(6): 630–36.

Dudeja S S, Giri R, Saini R, Suneja Madan P and Kothe E. 2012. Interaction of endophytic microbes with legumes. *Journal of Basic Microbiology* **52**(3): 248–60.

Gopalakrishnan S, Srinivas V, Alekhya G, Prakash B, Kudapa H, Rathore A and Varshney R K. 2015. The extent of grain yield and plant growth enhancement by plant growth-promoting broad-spectrum *Streptomyces* sp. in chickpea. *Springer Plus* **4**(1): 31.

Kan F L, Chen Z Y, Wang E T, Tian C F, Sui X H and Chen W X. 2007. Characterization of symbiotic and endophytic bacteria isolated from root nodules of herbaceous legumes cultivated in Qinghai-Tibet plateau and in other zones of China. *Archives of Microbiology* **188**: 103–15.

Korir H, Mungai NW, Thuita M, Hamba Y and Masso C. 2017. Co-inoculation effect of rhizobia and plant growth promoting rhizobacteria on common bean growth in a low phosphorus soil. *Frontiers in Plant Science* **8**: 141.

Li J H, Wang E T, Chena W F and Chena W X. 2008. Genetic diversity and potential for promotion of plant growth detected in nodule endophytic bacteria of soybean cultivated in Heilongjiang province of China. *Soil Biology and Biochemistry* **40**: 238–46.

Liu B, Qiao H, Huang L, Buchenauer H, Han Q, Kang Z and Gong Y. 2009. Biological control of take-all in wheat by endophytic *Bacillus subtilis* E1R-j and potential mode of action. *Biological Control* **49**: 277–85.

Nour S M, Fernandez M P, Normand P and Cleyet-Marel J C. 1994. *Rhizobium ciceri* sp. nov., consisting of strains that nodulate chickpeas (*Cicer arietinum* L.). *International Journal of Systemic Bacteriology* **44**: 511–22.

Olsen S R. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agriculture Circular **939**: 1–19.

Peoples M B, Ladha J K and Herridge D F. 1995. Enhancing legume N_2 fixation through plant and soil management. *Plant and Soil* **174**: 83–101.

Rangeshwaran R, Raj J and Kumar P S. 2008. Identification of endophytic bacteria in chickpea (*Cicer arietinum* L.) and their effect on plant growth. *Journal of Biological Control* **22**(1): 13–23.

Rosenblueth M and Martinez-Romero E. 2006. Bacterial endophytes and their interactions with hosts. *Molecular Plant-Microbe Interactions* **19**(8): 827–37.

Saini R, Kumar V, Dudeja S S and Pathak D V. 2015. Beneficial effects of inoculation of endophytic bacterial isolates from roots and nodules in chickpea. *International Journal of Current Microbiology and Applied Science* **4**(10): 207–21.

Soe K M, Bhromsiri A, Karladee D and Yamakawa T. 2012.Effects of endophytic actinomycetes and *Bradyrhizobium japonicum* strains on growth, nodulation, nitrogen fixation and seed weight of different soybean varieties. *Soil Science and Plant Nutrition* **58**(3): 319–25.

Subbiah B V and Asija G L. 1956. A rapid procedure for assessment of available nitrogen in soils. *Current Science* **31**: 196–260.

Swarnalakshmi K, Pooniya V and Paul S. 2017. Synergistic interaction of *Piriformospora indica* and microbial inoculants on symbiotic potential, plant nutrition and productivity of chickpea (*Cicer arietinum*). *Indian Journal of Agronomy* **62**(4): 481–88.

Swarnalakshmi K**,** Rajkhowa S, Senthilkumar M and Dhar D W. 2019. Influence of endophytic bacteria on growth promotion and protection against diseases in associated plants. *Microbial Interventions in Agriculture and Environment*, Vol. 3, pp 263–87. Singh D P and Prabha R (Eds). Springer Nature Singapore Pte Ltd, Singapore.

Swarnalakshmi K, Yadav V, Tyagi D, Dhar D W, Kannepalli A and Kumar S. 2020. Significance of plant growth promoting rhizobacteria in grain legumes: growth promotion and crop production. *Plants* **9**(11): 1596.

Valverde A, Burgos A, Fiscella T, Rivas R, Velaz-quez E, Rodriguez-Barrueco C, Cervantes E, Chamber M and Igual J M. 2006. Differential effects of coinoculations with *Pseudomonas jessenii* PS06 (a phosphate-solubilizingbacteria) and *Mesorhizobium ciceri* C-2/2 strains on the growth and seed yield of chickpea under greenhouse and field conditions. *Plant and Soil* **287**: 43–50.

Verma J P, Yadav J, Tiwari K N and Kumar A. 2013. Effect of indigenous *Mesorhizobium* spp. and plant growth promoting rhizobacteria on yields and nutrients uptake of chickpea (*Cicer arietinum* L.) under sustainable agriculture. *Ecological Engineering* **51**: 282–86.

Walkley A and Black I A. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic soil titration method. *Soil Science* **37**(1): 29–38.

Wani P A, Khan M S and Zaidi A. 2007. Synergistic effects of the inoculation with nitrogen-fixing and phosphate solubilizing rhizobacteria on the performance of field grown chickpea. *Journal of Plant Nutrition and Soil Science* **170**(2): 283–28.

Wolinska A and Stępniewska Z. 2012. Dehydrogenase activity in the soil environment. *Dehydrogenases*: 183–210.