Plant Interaction with Methylotrophic Communities

30

Manish Kumar, Raghvendra Saxena, Rajesh Singh Tomar,
and Pankaj Kumar Rai

Abstract

Methylotrophs are a diverse group of bacterial community utilizing a number of C1 carbon compounds as a source of carbon and energy. This peculiar group of microorganisms has capability to enhance plant growth by solubilizing phosphates, by producing siderophores, by inhibiting ethylene accumulation in plants in adverse conditions, by fixing atmospheric nitrogen, by producing phytohormones such as auxins and cytokinins, and by degrading various harmful and toxic compounds. The plant roots are colonized by different types of methylotrophic bacteria, and solubilized essential elements are provided to the plants making them healthier and strong. There are a number of beneficial biological interactions of methylotrophs with the plants. Interaction of methanotrophs with plants leads to the reduction in greenhouse effects in the environment. The interaction of methylotrophic bacteria with plants as endophytes, epiphytes, plant colonizers, phytohormone producers, and other types of beneficial association makes them very peculiar group of microbes interacting natural flora. Apart from higher plants, methylotrophic interaction was observed with bryophytes also as epiphytic as well as endophytic bacteria.

Keywords

Methylotrophs • PGPRs • Endophyte • Bacterial community • Phytohormone

---

M. Kumar (✉) • R. Saxena • R.S. Tomar
Amity Institute of Biotechnology, Amity University, Gwalior, Madhya Pradesh, India
e-mail: manishgsrivastava@gmail.com

P.K. Rai
Department of Biotechnology and Bioinformatics Centre, Barkatullah University,
Bhopal, India

D.P. Singh et al. (eds.), *Plant-Microbe Interactions in Agro-Ecological Perspectives*, https://doi.org/10.1007/978-981-10-6593-4_30

30.1 Introduction

Methylotrophic bacteria are ubiquitous, and a strong association and interaction with plants, within plants, and around the plant system is very common. They are abundantly present over plant leaf surfaces as pink-pigmented facultative methylotrophs. They participate in various plant-associated activities also. They can solubilize phosphate also and provide to the plants, promoting their growth. Plants in stress environment or extreme condition are influenced by this promising group of microbes. There are various novel potential methylotrophic bacteria reported to be in strong association with plants. They are also recognized as plant growth-promoting rhizobacteria, and several finding showed their colonization with plant roots. These specific reduced carbon-utilizing communities are present as both plant endophytes and epiphytes. Taking these considerations, methylotrophs associated with plants are here discussed with examples and recent developments.

30.2 Novel Methylotrophic Bacteria Associated with Plants

Like several novel bacterial strains, methylotrophic bacteria are also isolated from various ecosystems and reported novel after subsequent molecular characterization. Moreover, plant-associated epiphytic and endophytic methylotrophic strains were found to be novel after polyphasic approach. Most of the studies conclude *Methylobacterium* sp. as predominant plant-associated novel methylotrophic bacteria.

From *Populus delitoidesnigra* (poplar tree), a novel aerobic PPFM (pink-pigmented facultative methylotroph) was isolated and identified as *Methylobacterium* sp. strain BJ001T. The phylogenetic analysis revealed its relatedness with *Methylobacterium extorquens*, *Methylobacterium thiocynatum*, *Methylobacterium rhodesianum*, and *Methylobacterium zatmanii*. The carbon substrate utilization pattern of bacterium was differed from other phylogenetically closed methylotrophs, specifically methane carbon source (Aken et al. 2004).

Novel methylotrophic bacteria were isolated from leaf tissue of rice plant and were identified as *Methylobacterium oryzae* CBMB27T. Molecular chronometer 16S rRNA gene-based phylogenetic analysis revealed the taxonomic position of *Oryza sativa* L. CBMB27T in a clad of *Methylobacterium oryzae*, *Methylobacterium fujisawaense*, and *Methylobacterium mesophilicum* showed homology with 98.3%, 98.5%, and 97.3%, respectively. The experiment was validated by DNA-DNA hybridization together with polyphasic approaches to observe the relatedness of novel strain CBMB27T with its closest species (Madhaiyan et al. 2009b).

In an earlier finding, three novel restricted facultative methylotrophic bacterial strains 301 T, 30S, and SIP-4, utilizing C1 carbon compounds, were isolated from Lake Washington, Seattle, USA. Their phylogenetic position was determined by genotypic and phenotypic characterization using polyphasic approach. The above characterization method and results assigned SIP-3 strain as *Methylovorus glucosotrophus*, while strains 301 T and 30S were grouped in *Methylotenera mobilis*

JLW8T clad based on 16S rRNA gene sequence homology, but they were proposed as a novel strain *Methylotenera versatilis* sp. nov. based on their genomic and phenotypic characterization (Kalyuzhnaya et al. 2011).

Three different strains of methylotrophic yeast were isolated from leaf phylloplane of mango tree (*Mangifera indica*) and wine grapes (*Vitis vinifera*). Two strains KM13 and KM15 from grape leaf and one strain KM03 T from mango leaf were isolated. On the basis of various polyphasic characterization and nucleotide sequence-based phylogeny, these three strains were placed in the *Ogataea wickerhamii* clade. On the basis of various polyphasic approaches along with ITS region sequence analysis, strain KM03T was proposed as a novel species named *Ogataea kanchanaburiensis* sp. nov., while two other strains KM13T and KM15 were assigned as *Ogataea wangdongensis* sp. nov. (Limtong et al. 2013).

From wheat soil contaminated with tribenuron methyl, a novel bacterial strain was obtained. By the polyphasic approaches like phenotypic characterization, carbon substrate utilization, lipid estimation, G + C content analysis, DNA-DNA hybridization, and nucleotide-based phylogeny revealed this strain as *Methylopila henanense* sp. nov. This novel strain was placed in the clad of most closely related genus *Methylopila* after 16S rRNA gene sequence analysis (Wang et al. 2015). In an earlier finding, a novel bioinoculant for sustainable agriculture in the form of nonpathogenic phyllosphere methylotrophic bacteria was applied to agricultural fields to increase germination ability, storage ability, or seed vigor (Rajan et al. 2012).

30.3 Methylotrophs as PGPR (Plant Growth-Promoting Rhizobacteria)

Methylotrophs are well-known for their potential to minimize the biotic and abiotic stress factors affecting plants by their plant growth-promoting ability. Moreover, this subpopulation is indulged in the mechanism of plant growth promotion directly or indirecly.

Methylotrophic bacteria are also referred to as plant growth enhancer, and several species are isolated and reported earlier from rhizosphere region of plants (Meena et al. 2012; Anitha 2010; Madhaiyan et al. 2009a, b). In a study, methylotrophic bacteria having nitrogen-fixing ability were isolated from tropical legume plants *Sesbania aculeata* and *Crotalaria juncea*. Biochemical and molecular characterization identified the strain as *Methylobacterium nodulans* ORS2060. Under greenhouse condition, a significant increased nodulation in *C. juncea* and *M. atropurpureum* was observed along with higher nitrogenase activity (Madhaiyan et al. 2009a, b).

Looking at the potential of methylotrophic strains, a study was framed earlier to assess their plant growth-promoting ability together with the synergistic effect of methylotrophs, *Azospirillum*, and phosphobacteria. Investigation was done in a hybrid tomato plant CoTH1 under greenhouse condition. In pot experiment seeds were coated with the consortia of *Azospirillum* and phosphobacteria, while foliar spray of methylotrophs was also applied, and a significant growth and yield was recorded. Apart from plant growth-promoting rhizobacteria (PGPR), phyllosphere bacterial inhabitants have also an ability to enhance and promote plant growth (Basile et al. 1969). Methanol is assimilated to CO_2 by methylotrophs similar to plants, and therefore toxicity produced because of formaldehyde accumulation is avoided and reduced in plants (McGiffen and Manthey 1996).

Methylotrophs associated with crop plants are reported as nitrogen fixers (Lee et al. 2006; Madhaiyan et al. 2004), as biofertilizers (Keerthi et al. 2015; Rekadwad 2014; Chauhan et al. 2010), and as IAA-producing bacteria (Anitha 2010) and used as inoculants for making agriculture sustainable (Kumar et al. 2016). In an earlier investigation, bacterial species of genus *Methylobacterium* were isolated from leaf phyllosphere of different crop plants and identified with the help of functional gene sequences of mxaF gene. The HPLC analysis of culture filtrate confirms the cytokinin production from numerous *Methylobacterium* strains that enhance the seed germination and seed vigor of wheat plant. Such kind of plant growth regulator (cytokinin) producing potent methylotrophic bacteria can be exploited in the development of bioinoculants (Meena et al. 2012).

Plant root growth is regulated by a very specific compound ethylene, a pathway component of auxin biosynthesis (Hardoim et al. 2008; Madhaiyan et al. 2007). High ethylene concentration works as stress condition in plants that inhibit the root growth which leads to plant aging. ACC (aminocyclopropane-1-carboxylic acid) is the precursor of ethylene and converted to ethylene by the action of enzymes ACC synthase and ACC oxidase during auxin biosynthesis pathway. This higher concentration of ethylene is restricted by the bacterium converting ACC to ammonia and alpha ketobutyrate with the help of enzyme ACC- deaminase rather than ethylene. The *Methylobacterium* species such as *Methylobacterium oryzae* (Madhaiyan et al. 2007), *M. radiotolerans*, and *M. nodulans* (Fedorov et al. 2013) interact with different plant roots in stress environment, diminishing the stress effect and making plant healthier (Dourado et al. 2015; Glick 1995).

30.4 Methylotrophic Bacteria as Plant Colonizers

Methanol-utilizing pink-pigmented facultative methylotrophs, commonly found over the surface of plant leaves, are characterized by both biochemical and molecular approaches. The colonization of this PPFM population was observed in red clover and winter wheat leaves in a study. The more consistent colonization was observed in the isolates from red clover leaves. These microbial communities have the potential to colonize the plant rhizosphere also after inoculation of seeds (Omer et al. 2004).

The colonization of *Methylobacterium extorquens* was observed by gfp (green fluorescent protein) expression in an investigation (Figueira et al. 2000) in which transformation was reported with a gfp-containing plasmid under the control of methane monooxygenase and lacZ promoter. With the help of epifluorescence microscope, the colonization ability of *Methylobacterium* sp. was monitored in the study.

After seed bacterization the colonization of *Methylobacteria* in phyllosphere and rhizosphere was observed along with phyllosphere colonization after foliar spray was also studied. The experiment was validated and confirmed by site localization

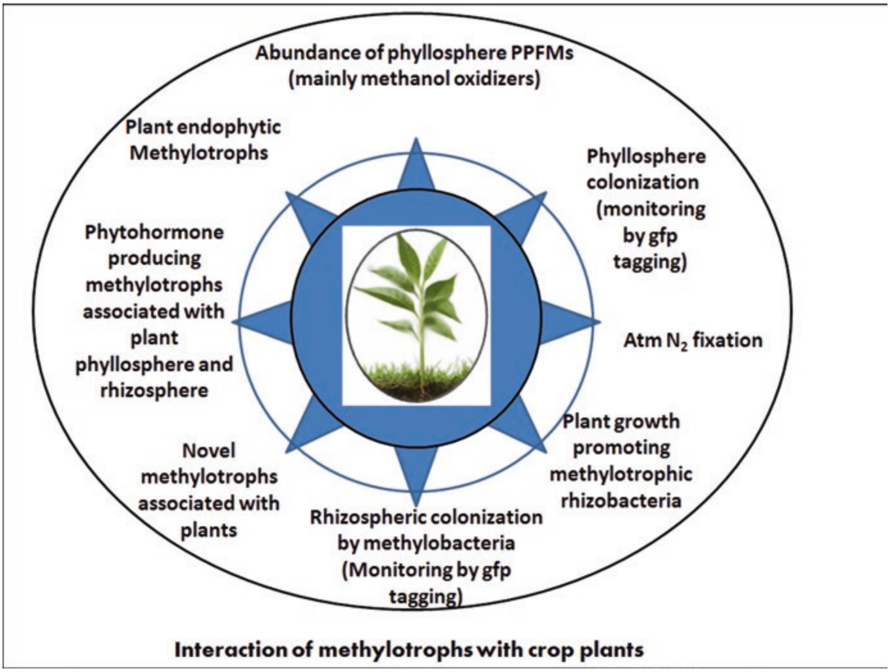

Fig. 30.1 Various interactions between plants and methylotrophic bacteria

of gfp-tagged mutants using confocal microscopy (Fig. 30.1). The abundance of *Methylobacterium* sp. was found in phyllosphere of wheat plant in an earlier investigation (Verma et al. 2014).

In another study on *Perilla* plant, the distribution and colonization of facultative *Methylobacterium* spp. was determined. *Perilla*, a herb, is widely used as food in Japan, and the interaction of this herb with methylotrophic bacteria was studied extensively. The distribution study of PPFM in different vegetable leaves results in the maximum abundance of methylotrophs over *Perilla* plant leaves and about 15% of the total bacterial inhabitants there. The isolates from the seeds of *Perilla* plant were identified as *M. fujisawaense* DSM5686T and *M. radiotolerans* JCM2831T, indicating a special type of interaction between PPFM and *Perilla* plant (Mizuno 2013).

The abundant methylotrophic bacteria over the plant surface actively participate in carbon dioxide fixation and affect the plant growth. The culture-independent assessment of three different plant phyllosphere bacteria using metaproteogenomic approach revealed predominant alpha proteobacterial genus *Methylobacterium* along with *Sphingomonas*. Soybean, clover, and *Arabidopsis* phyllosphere-associated *Methylobacteria* have the ability to utilize methanol as sole carbon and energy. The results show the identification of unique methylotrophic traits and therefore give a good example of plant-microbe interaction (Delmotte et al. 2009).

In a model legume plant, *Medicago truncatula*, colonization of methylotrophic bacteria especially *Methylobacterium* sp. was observed by an inoculation experiment.

The ability to utilize methanol as a source of carbon and energy provides a selective advantage at the time of colonization of model legume plant. The competitive colonization ability between mutant and wild type *Methylobacterium extorquens* AM1 was determined. The fluorescent protein-labeled *Methylobacterium extorquens* AM1 were observed under fluorescence microscopy which revealed the major bacterial communities on leaf surface while abundance on the lower leaf side (Sy et al. 2005).

Interaction of Methylotrophs with Water Plants Possibly, metabolite exchange between water plants and methylotrophs displays a beneficial interaction. Macrophyte-associated methanotrophs were found in the water column in a study where methanotrophs oxidize methane by utilizing oxygen released by plants, while CO_2 and ammonia are provided to plants by oxidation. Methane oxidation carried out by methanotrophs therefore reduces the greenhouse effect in the environment by this mutual relationship (Iguchi et al. 2015). Ultimately methylotrophic bacteria maintain the biogeochemical cycle of carbon in the ecosystem.

The community structure of methanotrophs associated with both dryland and flooded rice ecosystem was illustrated in earlier investigation. Molecular characterization-based community composition showed the abundance of Type I and Type II methanotrophic community in flooded rice field soils (Dubey and Singh 2001).

The PPFM (pink-pigmented facultative methylotroph) abundance apart from crop association was also observed with coastal region plants. Root region soil of different plant species of Southern California coastal region showed the PPFM abundance, that is, a best example of water plant-PPFM interaction. The PPFM abundance was in the range of 10^2–10^5 CFU/g dry soil of plant roots with variations across different plant species. In this natural ecosystem, this type of interaction suggests PPFM to be a better target for future work related to plant-microbe feedback. In the rhizosphere region of coastal sage scrub plants, PPFM abundance depends on both immediate and surrounding plant species (Irvine et al. 2012). Mangrove forest is another natural ecosystem of importance to mankind, and a diversified soil methylotrophic population was recorded from this fertile and dynamic ecosystem earlier. These potent methylotrophic strains have the ability to resist pathogenic fungus *Macrophomina phaseolina* (Kumar et al. 2015).

Wetlands are rich source of microbial assemblages, and this ecosystem is engaged in ecological control process. A number of methylotrophs are associated with wetland plants and are actively participating in nitrogen fixation process (Prasad et al. 2002; Barraquio and watanabe 1981). Fast accumulation of nitrogen in the roots of wetland plants indicates the methanotrophy during the development of peatland that ultimately induces the nitrogen fixation process. Additional CO_2 derived from methane is also fixed by methanotrophy in this ecosystem (Larmola et al. 2014). A novel methanotrophic bacterium *Methylocystis rosea* sp. from an arctic wetland soil of Norway was reported in a study having nitrogenase reductase structural gene (nifH) (Wartiainen et al. 2006).

30.5 Methylotrophs as Plant Endophytic Bacteria

This unique group of bacteria has properties to inhabit the plant internal compartments where they utilize methanol and other reduced carbon substrates to grow. They are actively participating in the metabolism of different plant metabolites. They are not pathogenic and are beneficial for plants in various aspects (Podolich et al. 2008; Pirttila et al. 2005; Madmony et al. 2005). Several endophytic bacterial communities are found within plant reproductive organs also (Madmony et al. 2005). The presence of endophytic methylotrophic bacteria induces the root formation along with enhanced biomass of soybean seedlings in a study (Holland and Polacco 1992). The endophytic bacteria reported in scots pine shoot tips were studied for their metabolic activity by in situ hybridization technique. These methylotrophic and other bacterial communities were found more abundant in summer season to the shoot tip and undetectable during winter season. This finding shows the temporal variation of the endophytic community, and highest endophytic numbers were also detected during spring season. The identified endophytic population in the shoot tip comprises *Methylobacterium* spp., *Pseudomonas fluorescens*, *Mycobacterium* sp., and *R. minuta*. Among all endophytic bacteria, *Methylobacterium* spp. was found most common and observed throughout the year (Pirttila et al. 2005) (Table 30.1).

Some another endophytic methylotrophs were observed and identified from poplar tree as *Methylobacterium populi* (Tanaka et al. 2008), and the location of the *Methylobacteria* inside the plant was examined through fluorescent in situ

Table 30.1 A list of endophytic and epiphytic methylotrophic bacteria associated with various plant or plant parts

S.No.		Plant/plant parts	References
Endophytic methylotrophs			
1.	*Methylobacterium* sp.	Seed seedlings	Ferreira et al. (2008)
2.	*Methylovorus mays*	Plant shoot	Ivanova et al. (2000, 2008)
	Methylobacterium mesophilicum		Ulrich et al. (2008)
3.	*Methylobacterium extorquens* str. F and *Pseudomonas synxantha* str. G	Bud endophyte of scots pine	Laukkanen et al. (2000) Pirttila et al. (2000, 2003)
4.	*Methylobacterium* sp. and *Pseudomonas fluorescens*	Shoot tip	Pirttila et al. (2002, 2005)
5.	*Methylobacterium radiotolerans*, *M. oryzae*, *M. fujisawaense*	Mangrove plants	Dourado et al. (2012)
6.	Methanotrophs	Stem leaves of *Sphagnum* mosses	Raghoebarsing et al. (2005)
7.	*Methylobacterium* sp.	Potato tissues	Podolich et al. (2008)
Epiphytic methylotrophs			
8.	*Methylobacterium extorquens* (trans-zeatin producing)	*Arabidopsis*, maize, barley, and soybean surface	Koenig et al. (2002)
9.	*Methylobacterium* sp.	Crop plants phyllosphere	Meena et al. (2012)
10.	*Methylobacterium* sp.	*Funaria* protonema	Hornschuh et al. (2002)

hybridization technique. Mangrove plants like *Rizophora*, *Laguncularia*, and *Avicennia* spp. were also reported to be associated with the methylotrophic communities such as *Methylobacterium radiotolerans*, *M. oryzae*, and *M. fujisawaense*. These strains were also reported with their heavy metal tolerance ability (Dourado et al. 2012).

30.6 Conclusion

Methylotroph-plant interaction is a best example of plant-microbe interaction that reflects the impact of this beneficial group of bacteria to environmental flora. The positive influence and interaction of methylotrophs with different parts of the plant make them healthier and strong enough in adverse conditions. Greenhouse effect also is inhibiting the growth of wider plant species in the environment, and methylotrophic communities (methanotrophs) are minimizing this plant growth-inhibiting effect. The abundant pink-pigmented facultative methylotrophic bacteria over plant leaf surface are also involved in plant growth promotion apart from rhizospheric methylotrophs. Plant-colonizing methylotrophic communities are also responsible for creating induced systemic resistance in plants. The present compilation enlightens the facts that endophytic or epiphytic methylotrophs interacting with various plant species and plant parts enhance our antiquity to know the physiological mechanism, activity, and abundance of methylotrophic communities.

Acknowledgments Manish Kumar, Raghvendra Saxena, and Rajesh Singh Tomar wish to express their sincere gratitude to Dr. Ashok Kumar Chauhan, President, RBEF parent organization of Amity University Madhya Pradesh (AUMP) for providing necessary facilities, as well as valuable support.

References

Aken BV, Peres CM, Doty SL, Yoon JM, Schnoor JL (2004) *Methylobacterium populi* sp. nov., a novel aerobic, pink-pigmented, facultatively methylotrophic, methane-utilizing bacterium isolated from poplar trees. Int J Syst Evol Microbiol 54:1191–1196

Anitha KG (2010) Enhancing seed germination of mono and dicotyledons through IAA production of PPFM. Trends Soil Sci Plant Nutr J 1:14–18

Barraquio WL, Watanabe I (1981) Occurrence of aerobic nitrogen-fixing bacteria in wetland and dryland plants. Soil Sci Plant Nutr Tokyo 27:121–125

Basile DV, Slade LL, Corpe WA (1969) An association between a bacterium and a liverwort, *Scapania nemorosa*. Bull Torrey Bot Club 96(6):711–714

Chauhan PS, Lee GS, Lee MK, Yim WJ, Lee GJ, Kim YS, Chung JB, Sa TM (2010) Effect of *Methylobacterium oryzae* CBMB20 inoculation and methanol spray on growth of red pepper (*Capsicum annuum* L.) at different fertilizer levels. Korean J Soil Sci Fert 43:514–521

Delmotte N, Knief C, Chaffron S, Innerebner G, Roschitzki B, Schlapbach R, Mering CV, Vorholt JA (2009) Community proteogenomics reveals insights into the physiology of phyllosphere bacteria. PNAS 10b(38):16428–16433

Dourado MN, Ferreira A, Araújo WL, Azevedo JL, Lacava PT (2012) The diversity of endophytic methylotrophic bacteria in an oil-contaminated and an oil-free mangrove ecosystem and their tolerance to heavy metals. Biotechnol Res Int 2012:759865

Dourado MN, Neves AAC, Santos DS, Araújo WL (2015) Biotechnological and agronomic potential of endophytic pink-pigmented methylotrophic *Methylobacterium* spp. Biomed Res Int. https://doi.org/10.1155/2015/909016

Dubey SK, Singh JS (2001) Plant-induced spatial variation in the size of methanotrophic population in dryland and flooded rice agroecosystems. Nutr Cycl Agroecosyst 59:161–167

Fedorov DN, Ekimova GA, Doronina NV, Trotsenko YA (2013) 1-Aminocyclopropane-1-carboxylate (ACC) deaminases from *Methylobacterium radiotolerans* and *Methylobacterium nodulans* with higher specificity for ACC. FEMS Microbiol Lett 343(1):70–76

Ferreira A, Quecine MC, Lacava PT et al (2008) Diversity of endophytic bacteria from Eucalyptus species seed and colonization of seedlings by *Pantoea agglomerans*. FEMS Microbiol Lett 287:8–14

Figueira MM, Laramee L, Murrell JC, Groleau D, Miguez CB (2000) Production of green fluorescent protein by the methylotrophic bacterium methylobacterium extorquens. FEMS Microbiol Lett 193:195–200

Glick BR (1995) The enhancement of plant growth by free-living bacteria. Can J Microbiol 41(2):109–117

Hardoim PR, Overbeek LSV, Elsas JDV (2008) Properties of bacterial endophytes and their proposed role in plant growth. Trends Microbiol 16(10):463–471

Holland MA, Polacco JC (1992) Urease-null and hydrogenase- null phenotypes of a phylloplane bacterium reveal altered nickel metabolism in two soybean mutants. Plant Physiol 98:942–948

Hornschuh M, Grotha R, Kutschera U (2002) Epiphytic bacteria associated with the bryophyte *Funaria hygrometrica*: effects of methylobacterium strains on protonema development. Plant Biol 4:682–687

Iguchi H, Yurimoto H, Sakai Y (2015) Interactions of methylotrophs with plants and other heterotrophic bacteria. Microorganisms 3:137–151

Irvine IC, Brigham CA, Suding KN, Martiny JBH (2012) The abundance of pink-pigmented facultative methylotrophs in the root zone of plant species in invaded coastal sage scrub habitat. PLoS One 7(2):e31026

Ivanova EG, Doronina NV, Shepelyakovskaya AO et al (2000) Facultative and obligate aerobic methylobacteria synthesise cytokinins. Mikrobiologiya 69:764–769

Ivanova EG, Pirttila AM, Fedorov DNF et al (2008) Association of methylotrophic bacteria with plants: metabolic aspects. In: Sorvari S, Pirttila AM (eds) Prospects and applications for plant associated microbes. A laboratory manual, part A: bacteria. Biobien innovations, Turku, pp 225–231

Kalyuzhnaya MG, Beck DAC, Vorobev A, Smalley N, Kunkel DD, Lidstrom ME, Chistoserdova L et al (2011) Novel methylotrophic isolates from lake sediment, description of *Methylotenera Versatilis* sp. nov. and emended description of the genus *Methylotenera*. Int J Syst Evol Microbiol 62(Pt 1):106–111

Keerthi MM, Babu R, Joseph M, Amutha R (2015) Optimizing plant geometry and nutrient management for grain yield and economics in irrigated green gram. Am J Plant Sci 6:1144–1150

Koenig RL, Morris RO, Polacco JC (2002) tRNA is the source of low level trans-zeatin production in *Methylobacterium* spp. J Bacteriol 184:1832–1842

Kumar M, Srivastava AK, Pandey AK (2015) Biocontrol activity of some potent Methylotrophs isolated from Bhitarkanika mangrove sediment. Int J Curr Res Biosci Plant Biol 2:101–106

Kumar M, Tomar RS, Lade H, Paul D (2016) Methylotrophic bacteria in sustainable agriculture. World J Microbiol Biotechnol 32:120

Larmola T, Leppänenb SM, Tuittilaa ES, Aarvab M, Meriläc P, Fritzed H, Tiirolab M (2014) Methanotrophy induces nitrogen fixation during peatland development. PNAS 111:734–739

Laukkanen H, Soini H, Kontunen-Soppela S et al (2000) A mycobacterium isolated from tissue cultures of mature *Pinus sylvestris* interferes with growth of Scots pine seedlings. Tree Physiol 20:915–920

Lee HS, Madhaiyan M, Kim CW, Choi SJ, Chung KY, Sa TM (2006) Physiological enhancement of early growth of rice seedlings (*Oryza sativa* L.) by production of phytohormone of N_2-fixing methylotrophic isolates. Biol Fertil Soil 42:402–408

Limtong S, Kaewwichian R, Groenewald M (2013) *Ogataea kanchanaburiensis* sp. nov. and *Ogataea wangdongensis* sp. nov., two novel methylotrophic yeast species from phylloplane in Thailand. Antonie Van Leeuwenhoek 103:551–558

Madhaiyan M, Poonguzhali S, Senthilkumar M, Seshadri S, Chung H, Yang J, Sundaram S, Sa T (2004) Growth promotion and induction of systemic resistance in rice cultivar Co-47 (*Oryza sativa* L.) by *Methylobacterium* spp. Bot Bull Acad Sin 45:315–325

Madhaiyan M, Poonguzhali S, Sa T (2007) Characterization of 1-aminocyclopropane-1-carboxylate (ACC) deaminase containing *Methylobacterium oryzae* and interactions with auxins and ACC regulation of ethylene in canola (*Brassica campestris*). Planta 226(4):867–876

Madhaiyan M, Poonguzhali S, Senthilkumar M, Sundaram SP, Sa T (2009a) Nodulation and plant-growth promotion by methylotrophic bacteria isolated from tropical legumes. Microbiol Res 164:114–120

Madhaiyan M, Poonguzhali S, Kwon S-W, Sas T-M (2009b) *Methylobacterium phyllosphaerae* sp. nov., a pink pigmented, facultative methylotroph from the phyllosphere of rice. Int J Syst Evol Microbiol 59:22–27

Madmony A, Chernin L, Pleban S et al (2005) *Enterobacter cloacae*, an obligatory endophyte of pollen grains of Mediterranean pines. Folia Microbiol 50:209–216

McGiffen ME, Manthey JA Jr (1996) The role of methanol in promoting plant growth: a current evaluation. Hortscience 31(7):1092–1096

Meena KK, Kumar M, Kalyuzhnaya MG, Yandigeri MS, Singh DP, Saxena AK, Arora DK (2012) Epiphytic pink-pigmented methylotrophic bacteria enhance germination and seedling growth of wheat (*Triticum aestivum*) by producing phytohormone. Antonie Van Leeuwenhoek 101:777–786

Mizuno M (2013) Studies on distribution and colonization of facultative methylotrophic bacteria *Methylobacterium* spp. on the perilla plant. Kyoto University Research Information Repository

Omer ZS, Tomboloni R, Broberg A, Gerhardson B (2004) Indole-3-acetic acid production by pink-pigmented facultative methylotrophic bacteria. Plant Growth Regul 43:93–96

Pirttila AM, Laukkanen H, Pospiech H et al (2000) Detection of intracellular bacteria in the buds of Scotch pine (*Pinus sylvestris* L.) Microb Ecol 45:53–62

Pirttilä AM, Pospiech H, Laukkanen H et al (2003) Two endophytic fungi in different tissues of scots pine buds (Pinus sylvestris L.) Microb Ecol 45:53–62

Pirttila AM, Laukkanen H, Hohtola A (2002) Chitinase production in pine callus (*Pinus sylvestris* L.): a defense reaction against endophytes? Planta 214:848–852

Pirttila AM, Pospiech H, Laukkanen H et al (2005) Seasonal variation in location and population structure of endophytes in bus of Scots pine. Tree Physiol 25:289–297

Podolich O, Laschevskyy V, Ovcharenko L, Kozyrovska N, Pirttila AM (2008) *Methylobacterium* sp. resides in unculturable state in potato tissues *in vitro* and becomes culturable after induction by *Pseudomonas fluorescens* IMGB163. J Appl Microbiol 106:728–737

Prasad SN, Ramachandra TV, Ahalya N, Sengupta T, Kumar A, Tiwari AK, Vijayan VS, Vijayan L (2002) Conservation of wetlands of India-a review. Trop Ecol 43(1):173–186

Raghoebarsing AA, Smolders AJP, Schmid MC, Rijpstra WIC, Wolters-Arts M, Derksen J, Jetten MSM, Schouten S, Damste JSS, Lamers LPM et al (2005) Methanotrophic symbionts provide carbon for photosynthesis in peat bogs. Nature 436:1153–1156

Rajan SA, Devi TS, Maina CC, Prathibaha K, Sundaram SP (2012) Methylotrophs – a novel bio-inoculant for sustainable agriculture. 6(3&4):141–144

Rekadwad BN (2014) Growth promotion of crop plants by *Methylobacterium organophilum*: efficient bio-inoculant and biofertilizer isolated from mud. Res Biotechnol 5:1–6

Sy A, Timmers AC, Knief C, Vorholt JA (2005) Methylotrophic metabolism is advantageous for *Methylobacterium extorquens* during colonization of *Medicago truncatula* under competitive conditions. Appl Environ Microbiol 71:7245–7252

Tanaka S, Walter KS, Schnoor JL (2008) Methods to investigate the role of endophytes in phytoremediation. In: Sorvari S, Pirttila AM (eds) Prospects and applications for plant associated microbes. A laboratory manual, Part A: Bacteria. Biobien Innovations, Turku, pp 325–332

Ulrich K, Ulrich A, Ewald D (2008) *Paenibacillus*- a predominant endophytic bacterium colonizing tissue cultures of woody plants. Plant Cell Organ Cult 93:347–351

Verma P, Yadav AN, Kazy SK, Saxena AK, Suman A (2014) Evaluating the diversity and phylogeny of plant growth promoting bacteria associated with wheat (*Triticum aestivum*) growing in central zone of India. Int J Curr Microbiol App Sci 3(5):432–447

Wang YN, Tian WY, He WH, Chen GC, An ML, Jia B, Liu L, Zhou Y, Liu SJ (2015) *Methylopila henanense* sp. nov., a novel methylotrophic bacterium isolated from tribenuron methyl-contaminated wheat soil. Antonie Van Leeuwenhoek 107(2):329–336

Wartiainen I, Hestnes AG, McDonald IR, Svenning MM (2006) *Methylocystis rosea* sp. nov., a novel methanotrophic bacterium from Arctic wetland soil, Svalbard, Norway (78° N). IJSEM 56:541–547