Research Review Article

Indian Journal of Agricultural Sciences **85** (4): 459–81, April 2015/Review Article

Exploiting nutrient-microbe synergy in unlocking productivity potential of perennial fruits : A review

A K SRIVASTAVA[1], S K MALHOTRA[2] and N K KRISHNA KUMAR[3]

ICAR-Central Citrus Research Institute, Amravati Road, Nagpur, Maharashtra 440 033

Recieved: 20 January 2015; Revised accepted: 6 February 2015

ABSTRACT

Fruits crops by the virtue of their nutritional qualities have already emerged as a major alternative, cutting short the menacing load on the consumption of traditional monotonous cereal/tuber crop-based diet. Huge microbial diversity has displayed different magnitude of synergism with fruit crops, which played a catalytic role in unlocking the productivity stagnation through improved efficacy of applied nutrients. Perennial fruit crops are better equipped to be benefitted through nutrient-microbe synergy because of their perennial framework and root configuration. However, use of multiple inoculation through crop specific microbial consortium, especially AM-based consortium in combination with nutrients (organic or inorganic in nature) provided a much better option in fruits with an added element of much better labile pool of microbial (taxonomic, function, and metabolic diversity) and nutrient pool of the rhizosphere for stronger soil carbon sink ultimately. The concept of "rhizosphere hybridization" is, therefore, advocated to harness the value added benefit of nutrient -microbe synergy, besides providing dynamism to microbial consortium suiting to wide range of perennial fruits. Microbial consortium augers well, with fertigation option as well, as a pretreatment of soil before injecting soluble mineral fertilizers into the wetting zone of drippers in order to improve upon the fertilizer use efficiency.

Key words : Fertigation, Fertilizer use efficiency, Microbial consortium, Nutrient-microbe synergy, Perennial fruits, Rhizosphere hybridization, Soil carbon sink

Perennial fruit crops represent hardly 1% of the global agricultural land area, but Mediterranean region covers maximum of 11% area, which are of great economic importance in world trade and tariff (FAO 2011). Approximately 1.7 million (2.8%) of deaths worldwide are attributable to micronutrient deficiency induced through lesser consumption of fruits and vegetables and regarded as top 10 selected risk factors for global mortality (WHO 2014). In the 21st century, nutrient efficient plants will play a major role in increasing crop yields compared to the 20th century, mainly due to limited land and water resources available for crop production, higher cost of inorganic fertilizer inputs, declining trends in crop yields globally, and increasing environmental concerns. Furthermore, at least 60% of the world's arable lands have mineral deficiencies or elemental toxicity problems, and on such soils fertilizers and lime amendments are essential for achieving improved crop yields (Pathak and Nedwell 2011). In the light of climate change related issuses, perennial fruit trees play an important role in carbon cycle of terrestrial ecosystems and sequestering atmospheric CO_2 (Lobell *et al.* 2005, Guimãres *et al.* 2014). According to Wu *et al.* (2012), net C sink and C storage in biomass of apple orchard ranged from 19 to 32 Tg C, respectively, and from 230 to 475 Tg C in 20 years period, amounting to 4.5% of total net C sink in the terrestrial ecosystems in China. In an estimate, Lakso (2010) observed that an acre of apple orchard fixed about 20 tonnes of CO_2 from the air each season, and provided over 15 tonnes of O_2, equivalent to over 5 billion BTU's of cooling power. While Mwamba (2013) showed that citrus trees carbon sequestration in biomass ranged from 23.9 tonnes CO_2/ha for young trees to 109 tonnes CO_2/ha for mature trees.

There will be an increasing importance of nutrient efficient cultivars that are higher producers. Nutrient efficient plants are defined as those plants, which produce higher yields per unit of nutrient, applied or absorbed than other plants (standards) under similar agroecological conditions. During the last three decades, much research has been conducted to identify and/or breed nutrient efficient plant species or genotypes/cultivars within different fruit species but the success in releasing nutrient efficient cultivars has been limited. The main reasons for limited success are that the genetics of plant responses to nutrients and plant

---

[1] Principal Scientist (Soil Science) (e mail: aksrivas2007@gmail.com), [2] Horticulture Commissioner (e mail: malhotraskraj@yahoo.com), Government of India, Ministry of Agriculture, Department of Agriculture and Cooperation, Krishi Bhawan, New Delhi 110 014; [3] Deputy Director General (e mail : kumariihar@yahoo.com; ddghort.@gmail.com), Division of Horticulture Science, ICAR, New Delhi 110 012

interactions with environmental variables are not well understood (Fageria *et al.* 2008). Fruit crops by the virtue of their perennial nature of woody framework (Nutrients locked therein), extended physiological stages of growth, differential root distribution pattern (root volume distribution), growth stages from the point of view of nutrien requirement and preferential requirement of some nutrients by specific fruit crop, collectively make them different than the annual crops (Srivastava *et al.* 2008, Srivastava 2013a, 2013b).

Plant growth promoting microorganisms play an important role exerting various mechanisms such as biological nitrogen fixation, growth hormone production, phosphate solubilisation siderophore production, hydrolytic enzymes production, antagonistic activity (Bunemann *et al.* 2006, Tailor and Joshi 2014). Activation of each mechanism implies the production of specific compounds and metabolites, such as plant growth factors, hydrolytic enzymes, siderophores, antibiotics, and carbon and nitrogen permeases. These metabolites can be either overproduced or combined with appropriate biocontrol strains in order to obtain new formulations for their more effective applications (Tahía *et al.* 2004). Studies have demonstrated that *Azotobacter* inoculation alone can substitute up to 50% nitrogen requirement of banana (Tiwari *et al.* 1999) and 25% phosphorus requirement of papaya (Padma and Kandasamy 1990). Arbuscular mycorrhizal fungi has also been reported to substantially improve nutrient acquisition capacity of host plant, and fruit yield in addition to enriching the rhizosphere biologically in a much activated form (Srivastava *et al.* 2002, Hazarika and Ansari 2007, Maity *et al.* 2012, Wu *et al.* 2013, 2014, Zhang *et al*. 2015, Liu *et al*. 2014, Huang *et al*. 2014, Zou *et al*. 2014a). Mineral fertilizers on the other hand have limited direct effects, but their application can enhance soil biological activity via increases in system productivity, crop residue return, and soil organic matter (Sankar *et al.* 2009, Khan *et al.* 2009, Khandelwal *et al.* 2013). Another important indirect effect especially of nitrogen fertilization is the soil acidification, with considerable negative effects on soil organisms (Chhonkar 2003). However, the outcome of a long-term fertilizer experiment in rice established that a balanced application of nutrients promoted microbial biomass through improved diversity of the microbial community (Zhang and Wang 2005). There are ample evidences accrued through worldwide research that nutrient-microbe synergy is the launching pad for any perennial plant to mobilise and accumulate the required nutrients as per the metabolic nutrient demand (Berg 2009, Shylaja and Rao 2012, Wu and Srivastava 2012). Rengel *et al.* (1996) observed that the total number of bacterial colony forming units increased in the rhizosphere of Zn-efficient genotypes of wheat under Zn-deficiency and in Mn-efficient genotypes under conditions of Mn-deficiency. In contrast, a Zn-deficiency treatment acted synergistically with the number of fluorescent *Pseudomonas* in the rhizospheres.

A still bigger question emerges, whether rhizosphere competent microbes could collectively contribute towards improved resilience of plant's rhizosphere (Wang *et al.* 2014). And if those microbes are so successful in promoting growth response, addition of starter nutrients in such combination may further magnify the magnitude of response called nutrient-microbe synergy. Our earlier studies have shown that rhizosphere effective microbes have the tendency to play multiple roles (Rao and Dass 1989, Srivastava 2012, Keditsu and Srivastava 2014, Wu *et al*. 2014) to overcome various biotic and abiotic stresses while interacting with an environment. A sound understanding of nutrient-microbe synergy could possibly lay a solid foundation in unlocking the productivity potential of perennial fruit crops, besides safeguarding the soil health, both physico-chemically as well as biologically. In this background, incise efforts have been made to analyse various aspects of nutrient-microbe synergy in giving the desired fillip to the productivity of perennial fruit crops.

INORGANIC FERTILIZER USE

Optimum soil fertility induced plant nutrition has a key role to maximise yield and quality production of perennial fruit crops. The fertilizer requirement of perennial fruit crops is determined by many approaches, including surveys, growers' experience, following the fertilization program of high yielding orchards, replacing the amount of nutrients removed by fruits, deficiency symptoms, applying results from sand or soil culture and field experiments and leaf/soil analysis, with each one of these having distinct advantages and limitations (Srivastava and Malhotra 2014).

Three approaches to fertilizer recommendations that are widely used: the deficiency correction philosophy (originates from nutrient constraints based crop response through nutrient additions to the point of maximum economic yield), maintenance concept (aims to maintain soil fertility level slightly above the point of maximum economic yield), and nutrient removal or balanced philosophy (emphasizes the return to the soil what is removed by the crop to maintain productivity, but often over recommends nutrient need, since it does not take into account for the soil's ability to supply available nutrients to the plants over time) (Srivastava *et al.* 2008, 2014b).

Soil fertilization – A conventional method

Soil provides nearly all the nutrients essential to complete the life cycle of a plant. Different soil properties primarily determine the extent of a fertilizer response (Bronick and Lal 2005) and the crop rotation on some recently published review articles changes in physico-chemical (Lehoczky *et al.* 2005) and biological properties of soil (Manna *et al.* 2005). Since the subject of fertilization in horticultural crops is so vast and complex, the readers may refer to the few review articles exclusively devoted to different issues of nutrient management in perennial fruit crops (Lipecki and Barbeæ 1997, Zahir *et al.* 2003, Hazarika and Ansari 2007, Srivastava and Singh 2008c, Berg 2009, Srivastava and Ngullie 2009, Maity *et al.* 2012, Singh *et al.* 2012, Srivastava 2012). However, the subject dealing with multipronged action to rhizocompetent microves in combination of various nutrient sources in fruit crops, is distinctly missing.

Optimum macronutrients: There are varied fertilization and doses schedules followed across a variety of crops (Table 1). Some fertilization plans recommend N application since the beginning of bud break until 6 weeks after full bloom for bearing pear trees (Neto *et al.* 2008), whereas others defend that N must be applied during the whole growth cycle considering that after harvest, trees can still improve their reserves through N uptake from soil. Some authors have studied the fertilizer N use efficiency in pears and apples (Cheng *et al.* 2001, Neilsen *et al.* 2001, Chen *et al.* 2004). Most studies were performed in pots in sand culture, comprising its applicability to field conditions. The recycling of N as a result of the decomposition of senescent leaves in soils was only addressed in one study with apple trees (Tagaliavini *et al.* 2004, 2007). Fertilizer N use efficiency by trees increased from the first to the third year, but was generally small (6, 14, and 33%), and estimated N losses were large (89, 46, and 53%, respectively, in the first, second, and third year). Irrigation water and soil provided more N to the trees than fertilizer N (Neto *et al.* 2008).

For many years, several authors have tested the response of different crops to application of different nutrients, especially K, with respect to yield and quality, in many crops like coffee, *Coffea arabica* L.(Silva *et al.* 2001); almond, *Amygdalus communis* L. (Reídel *et al.* 2004); pistachio, *Pistacio vera* L. (Zeng *et al.* 2001); pecan, *Carya illinoinensis* Koch (Worley 1994); olive, *Olea europaea* (Jasrotia *et al.* 1999) etc. However, such basal fertilizer application technique is greatly conditioned by different soil properties, particularly soil moisture, which affects the mobility of the supplied nutrients (Mengel and Kirkby 2000). This is mainly attributed to large variation in fertilizer doses to be really effective (Table 1) in different crops, annual versus perennial. Such variation in optimum doses is dictated by climate, soil types, crops, and farming practices in such a way that the correct balance of nutrients necessary for one farm, may be quite different from that necessary for a farm somewhere else in the world (Sarangthem *et al*. 2014). Therefore, determining the appropriate balance of nutrients to increase crop yield and soil fertility will require localized research.

Optimum micronutrients: Soil application of micronutrients, especially inorganic salts, is often not so effective due to immediate reaction of added micronutrient cations with the mineral portion of soil through various processes like adsorption, fixation, chemical precipitation, etc. (Srivastava and Singh 2008b) irrespective of crop, annual or perennial in nature. This issue in the past has been addressed in depth. Researchers even today are not unanimous about the efficacy of soil versus foliar fertilization with reference to micronutrients (Srivastava and Singh 2004, 2008b). Elevating Zn concentration only in the tops of Zn-deficient sour orange (*Citrus aurantium* L.) plants with foliar sprays partially restored normal root growth but clearly was not as effective as the roots absorbing Zn directly from high Zn concentration solutions (Swietlik and Zhang 1994). Duxbury *et al*. (2006) suggested that micronutrient-enriched seed successfully addressed Zn and Mo deficiencies in rice and wheat, and increased yields beyond those achieved by soil fertilization due to difference in root health activating early seedling emergence.

Interestingly, some recommendations have advocated soil application of micronutrients as one of the means to realize good yield of a crop, e.g. $ZnSO_4$ (300 g/tree) – $FeSO_4$ (300 g/tree) – 600 N – 200 P_2O_5 – 100 K (g/tree) in citrus (Srivastava and Singh 2008c, Srivastava and Patil 2014, Srivastava *et al.* 2014b). The micronutrient-based Zn chelater complexes on the other hand are poorly or not at all absorbed by plant roots, as demonstrated through water culture studies (Chaney 1988, Swietlik and Zhang 1994). Under field conditions, however, the addition of Zn micronutrient-chelate elevated the amount of exchangeable nutrients in the soil solution due to adsorption and exchange

Table 1 Optimum nutrient requirement for different fruit crops

Fruit crop (g/tree)	N	P_2O_5	K_2O	Reference
Mango (*Mangifera indica* L.)	800	200	300	Sharma *et al.* (2000)
Acid lime (*Citrus aurantifolia* Swingle L.)	800	200	100	Huchche *et al.* (1996)
Guava (*Psidium guajava* L.)	500	250	250	Singh and Singh (2007)
Grape (*Vitis vinifera* L.)*	300	500	1000	Patil *et al.* (2008)
Pomegranate (*Punica granatum* L.)	400	100	300	Ghosh *et al.* (2012)
Ber (*Zyzyphus mauritiana* Lank)	500	200	300	Lal *et al.* (2003)
Aonla (*Emblica officinalis* Gaertn)*	212	15	234	Biswas *et al.* (2012)
Sapota (*Achras zapota* Mill.)	400	100	300	Ghosh *et al.* (2012)
Date palm (*Phoenix dactylifera* L.)	460	500	500	Munir *et al.* (1992)
Fig (*Ficus carica* L.)**	430	200	430	Irget *et al.* (2008)
Phalsa (*Grewia subinaeuqualis* DC)	200	75	100	Sharma *et al.* (2008)
Apple ((*Malus domestica* Borkh.)	1065	650	1500	Singh *et al.* (2011)
Litchi (*Litchi chinensis* Sonn.)***	600	350	140	Pathak and Mitra (2008)
Pear (*Pyrus communis* L.)	1000	2000	1500	Arora and Singh (2006)

* Figures in kg/ha; ** Addition of 280 g/tree Ca; *** Addition of B at 7 g/plant

properties of minerals present in soil (Chaney 1988). Soil application of a micronutrient, e.g. Zn from $ZnSO_4$ is fixed in the surface soil, while the chelated-Zn remains soluble and becomes distributed evenly throughout the soil, as evident from 46-times higher uptake of Zn by a perennial fruit crop like citrus from Zn-EDTA than $ZnSO_4$ on sandy soils (Parker *et al.* 1995). In non-citrus crops like wheat (Modaihsha 1997), banana (Mostafa *et al.* 2007), pear, apple, grapevine (Sohlegel *et al.* 2006) etc. similar results have been reported. Of late, micronutrient seed treatment including seed priming and seed coating have offered an attractive and easy alternative (Farooq *et al.* 2012). One of the major obstacles of conventional practices of addressing nutritional requirements of perennial fruit crops, either through soil fertilization or through foliar feeding, is the precise diagnosis if the nutrient constraint type, their doses as per crop age and soil type, with the result more often such practices have not been able to facilitate the realisation of potential productivity of fruit crops. Neither any due consideration is given to exploit the nutrient reserve of the plant's rhizosphere (native nutrient supplying capacity of soil) while formulating the fertilizer doses. And most importantly in perennial fruit crops, nutrient doses need to be recommended in tandem with level of fruit yield targeted, a nutrient dose optimum for one fruit yield target, will become suboptimum for higher targetted fruit yield level in couple in subsequent years. Where is such nutrient monitoring tool to keep vigil on nutrient input and output relationship, a kind of nutrient budgeting (Srivastava 2013a, 2013b, Srivastava and Singh 2008a).

Large number of studies have, however, demonstrated much better fertilizer use efficiency with fertigation in crops like guava (Ramniwas *et al.* 2012), banana (Reddy *et al.* 2002), apple (Banyal and Sharma 2011), kiwifruit (Chauhan and Chandel 2008), sweet cherry (Ahmed *et al.* 2010), litchi (Dey *et al.* 2010), sapota (Khot *et al.* 2012), mango (Singh *et al.* 2009), banana (Pawar and Dingre 2013), citrus (Srivastava *et al*. 2003, Shirgure and Srivastava 2014a, 2014b, Yong-Ming *et al.* 2014), papaya (Jeyakumar *et al.* 2010), pomegranate (Haneef *et al.* 2014) etc. using various bases of drip irrigation scheduling and NPK-based fertilizers, but without much success with micronutrient fertigation. These studies have provided a wealth of information with unanimous result that fertigation reduced both irrigation and nutrient requirement by 30-50% compared to conventional split application within plant basin. Open hydroponics (Krugger *et al.* 2000, Martinez *et al.* 2004, Shirgure *et al.* 2014) and variable rate fertilizer linked site specific nutrient management (Zaman and Schumann 2006, Johnston *et al*. 2009, Srivastava *et al.* 2014b) in fruit crops like citrus, olive, avocado, coconut etc. have also started showing their utility in improving fertilizers use efficiency to various dimensions.

MICROBE-PERENNIAL CROP INTERACTION

Plant-associated microorganisms fulfill important functions for plant growth and health. Direct plant growth promotion by microbes is based on improved nutrient acquisition and hormonal stimulation. Members of the bacteria genera, *Azospirillum* and *Rhizobium* are well-studied examples for plant growth promotion, *Bacillus, Pseudomonas, Serratia, Stenotrophomonas*, and *Streptomyces* and the fungal genera *Ampelomyces, Coniothyrium*, and *Trichoderma* are model organisms to demonstrate influence on plant health. Based on these beneficial plant-microbe interactions, it is possible to develop microbial inoculants for use in fruit crops. Dependent on their mode of action and effects, these products can be used as biofertilizers, plant strengtheners, phytosimulators, and biopesticides. Altogether, the use of microorganisms and the exploitation of beneficial plant-microbe interactions offer promising and environment friendly strategies for sustainable development of fruit crops (Berg 2009). Significance of plant growth promotion and rhizosphere competence in biocontrol is also considered equally important (Whipps 2001).

Rhizosphere modification through roots by soil microorganisms exudation is an important attribute that regulates not only the availability of nutrients in the soil but also their acquisition by plants. A number of studies (Ferguson 1982, Graham and Timmer 1985, Roger 1991, Shamseldin *et al.* 2010, Esitken *et al.* 2006) have suggested that whole range of microorganisms including arbuscular mycorrhizal fungi (AMF) have helped to alleviate different nutritional deficiencies in fruit crops.

Analysis of rhizosphere microbial diversity

Size of the soil microbial pool is often expressed in terms of microbial biomass (Powlson *et al.* 1987, Powlson 1994). Vigour and yield of orange crop are affected by soil types due to variation in microbial population (Zou *et al.* 1994), cultivar type (Singh *et al.* 2002), and soil fertility (Yao *et al.* 2000). Rhizosphere soils of 19 fruit crop from a horticultural farm of Bangladesh Agricultural Research (BARI), Joydebpur, Gazipur were assessed for AM spore population and determining colonization in their roots. The spore numbers (100/g soil) ranged from 48 in lemon (*Citrus limon*) to 1 050 in custard apple (*Annona reticulata*) in 2004, which later increased from 41 in pummelo (*Citrus grandis*) to 962 in gooseberry (*Phyllanthus embica*) in 2005, and from 44 in pummelo (*Citrus grandis*) to 575 in wax apple (*Syzygium samarangense*) in 2006 (Khanam, 2007). Other studies reported that using a trap culture technique, 26 species (Gai *et al.* 2006) and as many as 60 species (Tchabi *et al.* 2008, Brundrett 2009, Wu *et al.* 2013) of AM were isolated belonging to six genera, *Glomus*, *Acaulospora*, *Paraglomus*, *Archaespora*, *Pacispora*, and *Scutellospora*. Despite soil being low or high in root colonizing population of AM propagules, a definite relationship exists between AM population and soil properties. The population of AM propagules in soil showed a positive correlation with soil properties such as N, organic C, available K, sand content, pH, and per cent AM root infection capacity, but a negative correlation with CEC, available P, silt, and clay content (Joshi and Singh 1995).

Studies on factors affecting the distribution of *Azotobacter* in acid soils of south India revealed the presence of *Azotobacter* in 35.2% of soils tested (Nair 1984). The SOM content showed no marked effect on the presence of these organisms, except at high levels when a universal correlation existed. A progressive increase in *Azotobacter* population was observed with increase in level of P due to lime application. Dehydrogenase and urease activity, microbial population (fungi and bacteria), and OM content of the soils increased with an increase in altitude up to 1100 m in Arunachal Pradesh, India (Tiwari and Sharma 1998). Gandotra *et al.* (1998) observed the presence of *Azotobacter* in 55 out of 66 soils studied in Himachal Pradesh (India) representing soil orders, viz. Mollisols, Alfisols, Ultisols, Inceptisols, and Entisols. The soils of Paleudalfs and Dystrochrepts were devoid of *Azotobacter*. Its population varied widely, constituting less than 1% of total bacteria. Haplustalfs and Hapludalfs had higher counts than other soil orders. Of the various soil properties positively correlated with *Azotobacter* population, a significant correlation was observed only with pH, available P, and exchangeable Mg^{2+}. Three species, viz. *A. chroococcum*, *A. beijerinckii*, and *A. vinelandi* were identified in these soils.

The occurrence of *Azospirillum* in the roots of a wide range of crops like cotton, plantation crops, and orchard crops has been reported under varying growing conditions (Bashan 1999). Subsequently, acid- and salt-tolerant strains have also been reported (Magalhães *et al.* 1983). So far taxonomists have identified many species in the genus *Azospirillum,* viz. *A. lipoferum*, *A. brasilense*, *A. amazonense*, *A. halopraeferens*, and *A. irakense* (Okon and Gonzalez 1994, Bhattacharya 2001), *A. doebereinrae* (Eckert *et al.* 2001), *A. melinis* (Peng *et al.* 2006), *A. canadense* (Mehnaz *et al.* 2007a), *A. zeae* (Mehnaz *et al.* 2007b), *A. rugosum* (Young *et al.* 2008), and *A. picis* (Lin *et al.* 2009). Among the free-living N-fixing bacteria, *Azospirillum* is considered to have more efficient nitrogenase properties than other N fixers. It has been well demonstrated that *Azospirillum*-inoculated plants were able to absorb nutrients from solution at faster rates than uninoculated plants resulting in accumulation of more dry matter, N, P, and K in the foliage (Okon 1985).

Soil microbial diversity besides being considered as one of the soil quality indices, undergoes frequent changes in response to management practices. Studies on medium term effects (12 years) on two management practices term sustainable (ST) and conventional (CT) on soil microbial composition and metabolic diversity of a rainfed mature olive orchard showed more culturable fungi, bacteria, metabolic diversity indices of microbial communities and soil enzyme activities in ST than in CT (Sofo *et al.* 2010b). Such changes in soil microbial communities responded significantly towards distinct improvements in olive fruit yield and quality (Sofo *et al.* 2010c). In another study in peach and kiwi fruit orchards, Sofo *et al.* (2010a) observed greater magnitude of qualitative and quantitative changes in soil microbial communities in response to an innovative (characterized by minimum tillage, organic matter inputs from composts and cover crops, water pruning and adequate irrigation and fertilization) than in conventional (characterized by conventional tillage, zero organic input, empirical pruning, strong chemical fertilization and excessive irrigation) soil management system.

A great variety of microbes, both as pure culture (as broth) as well as carrier-based cultures have shown their utility in diverse range of fruit crops (Table 2). These observations lend strong support that such effective microbes need to be fine tuned in combination with organic manures and inorganic fertilizers so that their more value added multi-dimensional response is visible in the context of perennial fruit crops.

Nitrogen fixing microbes

The rhizosphere supports large and active microbial populations capable of exerting beneficial, neutral, or detrimental effects of plant growth (Orhan *et al.* 2006). Plant growth promoting rhizobacteria (PGPR) was first described by Kloepper *et al.* (1989), as soil bacteria that colonize the roots of plants following inoculation onto seeds and that enhance plant growth. Later, Bashan and Holguin (1998) proposed two new terms, biocontrol plant growth promoting bacteria and plant growth promoting bacteria. *Azospirillum* and *Pantoea* are defined as free-living, plant-growth- promoting bacteria, capable of affecting the growth and yield in numerous plant species, many of agronomic and ecological significance (Bashan *et al.* 2004). Later, Herman *et al.* (2008) suggested *Bacillus* (*B. subtilis* and *B. amyloliquefaciens*)-based PGPR for simultaneously improved production in bell pepper and reduced aphid infestation in peach. These PGPR have no preference for crop plants or weeds, or for annual or perennial plants, and can be successfully applied to plants that have no previous history of PGPR in their roots (Dobbelaere *et al.* 2003). There is a general consensus that *Azospirillum* and plant roots can be described as a mere colonization of the rhizosphere, rhizoplane, and root interior (Govindarajan and Thangaraju 2001). The colonization is the result of a selective enrichment of the organism best adapted to the ecological niche formed by the root environment (showing both chemotaxis and chemokinesis), whose beneficial effects have been postulated to be partially due to production of phytohormones including GA_3, gibberellic acid (Cassan *et al.* 2001). The majority of bacteria are root colonizers, for example, *Azospirillum* has the ability to colonize at least 64 plant species (Bashan and Holguin 1995). Therefore, most of the studies demonstrated no host specificity in the *Azospirillum*-root association (Aseri *et al.* 2005, Tilak *et al.* 2005, Scheludko *et al.* 2009).

PGPR have been reported to enhance plant growth directly by a variety of mechanisms; fixation of atmospheric N that is transferred to the plant, production of siderophores that chelate Fe and make it available to the plant root, solubilization of minerals such as P, and synthesis of

Table 2 Response of different microbes on various growth, yield and nutrient uptake of fruit crops

Fruit crop	Microbes involved	Response parameters	Reference
Pomegranate (*Punica granatum* L.)	*Azotobacter chroococcum-Glomus mosseae*	Plant canopy, pruned material, rhizosphere changes and fruit yield	Mir and Sharma (2012)
Grape (*Vitis vinifera* L.)	*Pseudomonas fluorescens*	Root development	Wange and Ranawade (1998)
Quince (*Cydonia oblonga* Mill.)	*Bacillus mycoides-B. subtilis*	Fruit firmness, soluble dry matter and fruit yield	Arikan *et al.* (2013)
Navel orange (*Citrus sinensis* (L.) Osbeck)	*Pseudomonas fluorescens* (843)-*Azospirillum brasilense* (W24)	Canopy volume and soil fertility	Shamseldin *et al.* (2010)
Apple (*Malus domestica* Borkh.)	*Azotobacter chroococcum-Pseudomonas striata-Trichoderma viride*	Germination, root growth, and pest incidence	Raman (2012)
Peach (*Prunus persica* (L.) Stokes)	*Azospirillum brasilense Bacillus megatarium*	Plant height, girth and canopy growth	Mahmoud and Mahmoud (1999)
Peach (*Prunus persica* (L.) Stokes)	*Glomus fasciculatum – Azotobacter chroococcum*	Plant height, girth and micronutrient concentration	Godara *et al.* (1996)
Pomegranate (*Punica granatum* L.)	*Azotobacter chroococcum-Glomus mosseae*	Plant height, pruned material and fruit yield	Aseri *et al.* (2008)
Apple (*Malus domestica* Borkh.)	*Bacillus*(OSU 142,M-3)-*Pseudomonas*(BA-8)	Tree growth and fruit yield	Aslantas *et al.* (2007)
Mango (*Mangifera indica* L.)	*Azotobacter chroococcum*	Seedling diameter and number of leaves	Kerni and Gupta (1986)
Passion fruit (*Passiflora edulis* Sims.)	*Azotobacter* sp.-*Azospirillum* sp.-*Trichoderma* sp.	Improved plantlet growth and yield	Quiroga-Rojas *et al.* (2012)
Sweet orange (*Citrus sinensis* Osbeck)	*Azospirillum brasilense-Glomus fasiculatum*	Growth, fruit yield and nutrient uptake	Singh and Sharma (1993)
Banana (*Musa acuminata* L.)	*Azospirillium* sp.	Height and girth of pseudo-mostem, leaf area and yield	Jeeva *et al.* (1988)
Banana (*Musa acuminata* L.)	*Azotobacter chroococcum-Azospirillum brasilense*	Number of fingers, bunch weight and leaf area	Tiwari *et al.* (1999)
Banana (*Musa acuminata* L.)	*Azospirillum brasilense-Pseudomonas fluorescens*	Fruit weight and finger size	Suresh and Hasan (2001)
Sweet cherry (*Prunus avium* L.)	*Pseudomonas* (BA-8) and *Bacillus* (OSU-142)	Growth, yield and leaf nutrient composition	Esitken *et al.* (2006)
Apple (*Malus domestica* Borkh.)	*Bacillus* (M3)-*Bacillus* (OSU-143)- *Microbacterium*	Growth, yield and plant nutrition	Karlidag *et al.* (2007)
Apricot (*Prunus armeniaca* (L.))	*Bacillus* (OSU-142)	Shoot length, yield and leaf nutrient concentration	Esitken *et al.* (2003)
Apricot (*Prunus armeniaca* (L.))	*Bacillus* (OSU-142)-*Pseudomonas*(BA-8)	Growth, yield and leaf nutrient composition	Pirlak *et al.* (2007)
Nagpur mandarin (*Citrus reticulata* Blanco)	*Bacillus mycoides- B. polymyxa, Trichoderma harzianum-Azotobacter chroococcum-Pseudomonas fluorescens*	Shoot weight, root weight and rhizosphere microbial properties	Keditsu and Srivastava (2014)
Walnut (*Juglans hegia* L.)	*Pseudomonas chlororraphis-P. fluorescens- Bacillus cereus*	Plant height, shoot and root dry weight	Xuan Yu *et al.* (2011)
Papaya (*Carica papaya* L.)	*Glomus mosseae-G. fasciculatum Gigaspora margarita*	Growth and nutrient uptake	Padma and Kandasamy (1990)

phytohormones (Dobbelaere *et al.* 2001). Direct enhancement of mineral uptake due to increases in specific ion fluxes at the root surface in the presence of PGPR has also been reported (Bertrand *et al.* 2000, Tilak *et al.* 2005). Okon and Gonzalez (1994) evaluated worldwide data accumulated over the previous 20 years on field inoculation with *Azospirillum,* and concluded that these bacteria are capable of promoting the yield of crops in different soils and climatic area. *Azospirillum* spp. are involved in the biological fixation of N and the increased activity of glutamate dehydrogenase and glutamine synthetase (Ribaudo *et al.* 2001, Thuler *et al.* 2003). *Azospirillum brasilense* produces high quantities of extracellular indole-3-acetic acid (IAA), increasing root elongation, root surface area, and root dry matter (Molla *et al.* 2001). Basu *et al.* (2006) suggested that a small amount of chemical fertilizer like Co (0.2 kg/ha) showed a triggering effect on the efficacy of *Rhizobium* in groundnut (*Arachis hypogaea* L.).

Nitrogen-fixing bacteria and AM fungi were found to enhance the growth and production of various fruit plants significantly (Khanizadeh *et al.* 1995, Ghazi 2006) besides improving the microbial activity in the rhizosphere (Kohler *et al.* 2007). Aseri *et al.* (2008) observed that the combined treatment of *Azotobacter chroococcum* and *Glomus mosseae* was found to be the most effective since, besides enhancing the rhizosphere microbial activity and concentration of various metabolites and nutrients, these bioinoculants helped in better establishment of pomegranate plants under field conditions. According to some studies (Okon and Labandera-Gonzalez 1994, Bashan and Holguin 1997), response of microbial biofertilization is highly unpredictable results due to their biological origin and susceptibility to various abiotic stresses, besides difficulty in adjusting the inoculated microorganisms into new soil environment. However, considering the vital role of microbes in the maintenance and buildup of soil fertility, their utility is indispensable (Badiyala *et al.* 1990).

Phosphate solubilising microbes

In 1903, Stalatrom first reported microbial involvement in the solubilisation of inorganic phosphate (Panda 1990). During 1907-1908, Sacket, along with other scientists confirmed the solubilising capacity of different microorganisms (Gaur 1990). These phosphate-solubilising microorganisms popularly known as PSM involve phosphate sources, mainly of two types, i e i. mineral (fluorapatite, hydroxyapatite, tircalcium phosphate, mono- and dicalcium phosphate, rock phosphate, and iron phosphate) and ii. organic nature (phytin, lecithin, hexose monophosphatic ester, phenyl phosphate, and calcium glycerophosphate). The highly populated PSM produce significant quantities of organic acids as metabolic by-products (Bhattacharya and Jain 2000) namely formic, citric, acetic, propionic, malic, succinic, fumaric, glycolic, gluconic acid, etc. (Dubey and Gupta 1996, Dubey *et al.* 1999) depending on various C substrates. These organic acids are sources of biologically generated H^+ ion, dissolve mineral phosphate, and make it available to plants. The degree of phosphate solubilisation is further influenced by pH, Eh, O_2, CO_2 concentration, and by the presence of organic material in the growing media. Sometimes these acids form a unionised association with meal (chelation) and increase the concentration of soluble phosphate (Gyaneshwar *et al*. 2002). Many heterotrophic microorganisms are known to have some ability to solubilize inorganic P from insoluble sources (Gaur and Gaind 1992). Microbial solubilization of insoluble phosphates has also been reported through acidification, chelation, ion exchange reactions and external and internal accumulation of Ca^{2+} besides cell death lysis (Kucey 1983).

Various species of *Trichoderma* as dual purpose microbe (phosphate solubilizer as well as microbial antagonist) were also effective in the promotion of growth and yield in various crops (Bal and Altintas 2006a). Both the species of *Trichoderma*, viz. *T. harzianum* and *T. virens* promoted growth of cucumber and cotton seedlings (Yedidia *et al.* 2001), sweet corn (Bjorkman *et al.* 1998), cucumber, bell pepper, and strawberry (Altintas and Bal 2005, Bal and Altintas 2006b, Elad *et al.* 2006). On the other hand, application of *Trichoderma* was not conducive to increased yields of some annual crops like tomato (Bal and Altintas 2006c), lettuce (Bal and Altintas 2008), and onion (Poldma *et al.* 2001), suggesting some kind of inconsistency in response. However, other previous studies obtained significant yield increase in cucumber and bell pepper using a much higher dosage of P_2O_5 as 40 kg/ha (Altintas and Bal 2008).

Potassium solubilising microbes

Unfortunately, many studies carried out in the past have not been given due consideration due to exploitation of the potassium solubilising ability of microbes. A critical review by Mishustin *et al.* (1981) stated that although K is released from silicates by microorganisms, the process is not active enough to complete provision of the plants with this element. In K-deficiency, the increased root exudation accompanied by accelerated microbial proliferation and respiration may lead to O_2 depletion in the rhizosphere, thus favouring denitrification specifically (Merckx *et al.* 1987, Van Veen *et al.* 1989).

Some microorganisms in soil environment contain enzymes that function in ways analogous to chitinase and celluloses, i.e. they specifically break down mineral structure (Barker *et al.* 1997). Laboratory studies have shown that microbes can increase the dissolution rate of silicate and aluminum silicate minerals, primarily by generating organic and inorganic acids (Barker *et al.* 1997). Although some of these organisms are free-living (planktonic) in solution, most of these bacteria are attacked to mineral surfaces (Hazen *et al.* 1991, Holm *et al.* 1992), where they can impact water-rock interaction, mineral surface chemistry, dissolution and precipitation of minerals, the evolution of ground water geochemistry and soil formation (Barker and Banfield 1998, Neslson and Stahl 1997). Complete microbial respiration and degradation of particulate and dissolved organic C can elevate carbonic acid concentration at mineral surfaces, in soils and ground water (Barker *et al*. 1998), which can lead to an increase in the rates of mineral weathering by a proton-promoted dissolution mechanism. In addition to carbonic acid, microbes can produce and excrete organic ligands by a variety of processes such as fermentation and degradation of organic macromoleules, or as a response to nutrient stress (Paris *et al.* 1996). The reports showed that silicates dissolving bacteria could activate soil P, K, Si reserves and promote plant growth

(Xue *et al.* 2000, Sheng *et al.* 2003). Styriakova *et al.* (2003) reported that the activity of silicate dissolving bacteria played a pronounced role in the release of Si, Fe, and K from feldspar and Fe-oxyhydroxides.

Microbial solubilisation of micronutrients

Microorganisms attached to soil mineral surfaces ably create micro-environments where concentration of ligand, acidity and redox activity is substantially improved compared to the bulk soil, thus effecting mineral exchange reactions (Rogers *et al.* 1998, Barker *et al.* 1998). A large number of ligands, are not only oxalate but also pyruvate, citrate, succinate, malate, gluconate, lactate and fumarate have been detected in soils and on weathered rocks colonized by bacteria and fungi (Baker *et al.* 1986, Baziramakenga *et al.* 1995, Krzyszowska *et al.* 1996). The so-called fluorescent pseudomonads *Pseudomonas aeruginosa*, *P.fluorescens*, and *P.putida* produce a water-soluble yellow-green fluorescent (under UV light) pigment called pyoverdine (Meldrum 1999). This pigment is responsible for the characteristic fluorescence of the cell and has also been identified as an iron-chelating siderophore (Neilands 1983, Fernandez *et al.* 1988).

Another important factor for the colonization of plant roots, especially under iron-limiting condition, is the synthesis of siderophores from *Pseudomonas*, which are iron-chelating compounds (Cornelis 2010). Pseudomonas siderophore have a high affinity for iron, and when they chelate this micro-nutrient, they make it less available for other microorganisms, including plant pathogens (Kloepper *et al*. 1980, Weller 2007). This mechanism is considered in direct plant growth promotion by *Pseudomonas.* In particular, *Pseudomonas* can synthesizes siderophores in iron-limiting conditions, being a factor that induces gene expression in operons involved in siderophore synthesis. Other environmental factors such as pH, presence of trace element nitrogen, phosphorus and carbon are also important (Duffy and Defago 1999). It is known that compounds such as siderophores are synthesized mainly during the exponential growth phase, which is the stage in which the population requires more nutrients for cell division (Loper and Schroth 1986, O'Sullivan and O'Gra 1992). Likewise, the pseudofactor-Fe complex has a high stability constant (Chen *et al.* 1994). Other studies suggested that virtually all excreted pseudobactin molecules bind to Fe present in the medium. This complex acts as a Fe (III) delivery system for its introduction through bacterial cells (Koster *et al.* 1995, Loper and Henkels 1999). Therefore, in micronutrients such as rhizosphere, the synthesis of siderophores is important to confer an advantage in the competition for nutrients and space (Loper and Henkels 1999).

Trichoderma species are not only found to solubilize phosphorus but other important nutrients- through various mechanisms. They react to limiting iron conditions by using a high-affinity iron uptake system based on the release of iron chelating molecules called siderophores. This chelated iron is not available to plant pathogens, whose activity is thereby reduced (Baker *et al.* 1986), while plant roots can take up chelated irons either directly or after reduction of Fe^{3+} by plasma membrane reductases (Welch *et al.* 1993). *Trichoderma* has been found to evolve mechanisms that are involved in solubilization of Mn. Manganese can occur in several oxidation states, but it is available to plants only in the reduced form (Mn^{2+}). Higher oxidation states are insoluble. The oxidation state of soil Mn depends on both the soil condition (pH values below 6 favor reduction and values above 6.5 favor oxidation) and the activity of rhizosphere microorganisms that can either oxidize or reduce manganese and thus influence its availability (Huber and McCay-Buis 1993). Thus, microbial interactions with plant roots are known to profoundly affect plant nutrient status. If some strains of *Trichoderma* possess the ability to solubilize many different nutrients, it would not be surprising to find that multiple mechanisms are involved, even for a single element. For example, solubilization of iron may involve reduction of Fe^{3+} to Fe^{2+} as well as chelation of Fe^{3+} by siderophores or chelating agents (Wu *et al.* 2013).

Mycorrhizae have also been helpful in improving the uptake of diffusion limited micro nutrients such as P, Zn, Cu, Mn, and Fe by the host plants (Tinker 1982, Johnson 1984, Tang *et al.* 1984, Graham 1986) on account of their ability to dissolve and promote absorption of these elements (Englander 1981). This is accomplished primarily by extension of root geometry through symbiotic association in which fungus utilizes carbohydrates produced by the host plants, and plants in turn benefit by increased nutrients uptake, especially noticeable in soils of low fertility (Nemec 1979). Graham and Fardelmann (1986) observed higher uptake of Cu by Carrizo citrange inoculated with *Glomus intraradices* while El-Maksoud *et al.* (1988) observed greater uptake of N, P, Fe, Mn, and Zn by roots and aerial parts of sour orange seedlings inoculated with *Glomus* and *Gigaspora* sp. of mycorrhizal fungi in both calcareous and sandy soils of Egypt. Treeby (1992) observed increase in shoot Fe concentration in mycorrhized over non-mycorrhized citrus trees, more efficiently in an acidic environment. The exact mechanism of such cause and effect is still not clear, whether the endophyte is directly involved in Fe uptake, and supply to the host, or it is an indirect effect of the change in root growth habit. In another study, Onkarayya and Sukhada (1993) observed higher concentrations of P, N and Zn in AM inoculated rootstock seedlings of rough lemon (*Citrus jambhiri*), Rangpur lime (*Citrus limonia*), *Poncirus trifoliata*, Troyer citrange, Carrizo citrange, Citrumelo excluding Cleopatra mandarin. Mycorrhizas, especially *Glomus mosseae* in combination with *Pseudomonas fluorescens* has been observed to improve the Fe-efficiency in grapevine ungrafted rootstocks (Bavereco and Fogher 1992) and in grafted grape (Bavareco and Fogher 1996a, 1996b) under calcareous soil conditions.

Microbial consortium : A novel concept

Analysis of rhizosphere microbial diversity provides a valid clue for rhizosphere hybridization (Nothing but isolating and characterizing the rhizo-competent microbes from diverse crop rhizosphere and developing a competent group of microbes called microbial consortium) in order to infuse desired changes in rhizosphere microbial composition and consequent changes in nutrient availability. The most common objective of developing microbial consortium is to capitalise on both the capabilities of individual microbes and their interactions to create useful systems in tune with enhanced productivity and, soil health improvements through efficient metabolic functionality (Brenner *et al.* 2008). Two major underlying principles are applied in the whole process of development of microbial consortium. The first one is resource ratio theory which uses both qualitatively and quantitatively in order to assess the outcomes between component microorganisms competing for shared limiting resources. This permits coexistence of multiple microbes or the competitive exclusion of all but a single microbe (Brauer *et al.* 2012). And the second principle theory relevant to microbial consortium is maximum power principle initially proposed by Lotka (1992) and later modified at various levels, is value for analysing consortial interactions. It also dictates that biological systems that maximise fitness by maximising power, is analogous to metabolic rate or the capacity to capture and utilise energy (Sciubba 2011). The microbial consortium is classified (Handelsman *et al.* 1998, Kim *et al.* 2008, Klitgord and Segre 2011) as artificial (carrying two or more wild type microbes whose interactions do not typically occur naturally), synthetic (carrying microbes which are modified through manipulations of genetic content) and natural (carrying microbes having much wider applications like bioremediation, wastewater treatment, biogas synthesis etc.).

In a microbial consortium, there are different consortial interaction motifs which by and large, comprise of division of labor as functional differentiation and specialisation (Briones and Raskin 2003), synergistic division of resources, each component serving as carbon or energy source (Crespi 2001), commensalism where one component microbe provides an ecological niche for others at no benefit or cost to itself (Rosche *et al.* 2009), mutualistic, a relationship benefitting all component microbes (Wintermute and Silver 2010) and syntrophy defined as resource exchanges or cross feeding amongst component microbes (Shou *et al.* 2007).

Coinoculation or combined inoculation of different microbe types is another area which can be gainfully exploited in formulating the microbially-rich substrate, provided that information on the synergism between different microbes is known (Marschner *et al.* 2004). In the past, a number of studies have suggested the coinoculation of different microbes, which can be summarized as: *A. brasilense – P. striata/B. polymyxa* in sorghum (Alagawadi and Gaur 1992), *A. lipoferem – Agrobacterium radiobacter/ A. lipoferem-Arthrobacter mysorens* in barley (Belimov *et al.* 1995), *A. brasilense – Rhizobium* in lentil (Yadav *et al.* 1992) and chickpea (Fabbrie and Del Gallo 1995), *A. brasilense – A. chroococcum – Klebsiella pneumoniae – R. meliloti* in alfalfa (Hassouma *et al.* 1994), *A. brasilense – R. leguminosarum* in soybean (Neyra *et al.* 1995), and *A. brasilense/Streptomyces mutabilis – A. chroococcum* in wheat (Elshanshoury 1995). Many studies on coinoculation of microbes involving AM fungi and bacteria have also been suggested for improvement in both yield and quality. These include: *A. brasilense – G. fasciculatum* in wheat (Gori and Favilli 1995), strawberry (Bellone and de Bellone 1995), *A. brasilense – Pantoea dispersa* in sweetpepper (Amor *et al.* 2008), and *A. chroococcum – G. mosseae* in pomegranate (Aseri *et al.* 2008). The effectivensss of these co-inoculation studies warrant further studies on exploiting the added benefit of rhizosphere hybridization.

Growth promoting microbes were isolated from rhizosphere (0-20 cm) for development of MC through extensive soil sampling (from the rhizosphere of as many as 110 plants) at the experimental site. The microbial diversity existing within rhizosphere soil was isolated following standard procedures, and characterized the promising microbes for their nutrient mobilizing capacity through laboratory-based incubation study using the same experimental soil. The efficient microbes, viz. *Azotobacter chroococcum* (asymbiotic N-form*), Bacillus mycoides* (K-solubilizer), *Pseudomonas fluorescens* (P-solubilizer*), Bacillus polymyxa (*P-solubilizer), and *Trichoderma harzianum* (P-solubilizer) were finally identified. Pure culture of these microbes in value added form was developed in broth, and prepared a mixture called MC. The compatibility amongst these microbes was tested thoroughly by their population dynamics in consortium mode which showed no antagonism amongst them up to 90 days of laboratory oriented incubation study (Srivastava *et al.* 2014a). Inocualtion with microorganisms under pot culture conditions, has shown promising changes in soil properties, viz. water stable aggregate formation, soil enzymes, glomalin related Bradford protein as glue agent binding soil particles etc. using citrus as test crop (Wu *et al.* 2013, Zou *et al.* 2014b).

The response of microbial consortium on rough lemon seedlings (*Citrus jambhiri* Lush) showed a significant increase in various growth parameters over control. The inoculation with microbial consortium brought a significant change in available supply of different nutrients in soil and microbial biomass nutrients (Table 3). A significantly higher soil fertility status with microbial consortium treated plants was observed compared to untreated control. Similarly, microbial biomass nutrients were higher in the rhizosphere treated with microbial consortium than untreated control. The above observations strongly supported the effectiveness of microbial consortium in improving chemical and biological indices of citrus rhizosphere (Srivastava *et al.* 2014a).

Carrier-based substrate: Consistent efforts are being made to find alternatives to conventional fertilizers, media and practices, although chemical properties of formulated substrates may affect plant growth and nutritional response in varied ways. These comprise of : i. improvement in soil hydraulic properties, ii. maintenance of better available

Table 3 Response of microbial consortium on growth, soil fertility changes and soil microbial biomass nutrients in rough lemon seedlings treated for 45 days

Treatment	Growth		Soil available nutrients (mg/kg)							SMBN (mg/kg)		
	Root wt. (g)	Shoot wt. (g)	N	P	K	Fe	Mn	Cu	Zn	C_{mic}	N_{mic}	P_{mic}
Control	2.99	9.08	116.2	13.2	166.7	8.8	6.7	1.12	0.62	119.8	21.8	13.5
Treated	9.59	24.86	123.4	16.2	169.7	13.7	10.2	1.16	0.88	147.7	34.1	17.8
LSD (P=0.05)	3.65	5.63	3.95	2.0	NS	1.75	1.35	NS	0.12	9.85	2.5	1.25

- Computed on the basis of analysis after 162 days of inoculation. - SMBN stands for soil microbial biomass nutrients. Cmic, Nmic, and Pmic stand for soil microbial biomass-C, soil microbial biomass-N, and microbial soil biomass-P, respectively.

Source: Wu and Srivastava (2012); Keditsu and Srivastava (2014).

pool of nutrients, and iii. establishment of dynamic soil microbial environment, more suited to crop requirement (Dutt *et al.* 2002, Altland and Buamscha 2008). The origin of a substrate and its pH are considered two most important guiding principles in developing a substrate dynamic to plant's rhizosphere in addition to physical stability, ease in rewetting ability to withstand compression, and low shrinkage rate over time (Roose and Haase 2000, Altland 2006). Dutt and Sonawane (2006) observed excellent performance of chrysanthemum (*Chrysanthemum indicum* L.) on a substrate containing cocoa-peat-compost-rice husk. Recently, studies (Buamscha *et al.* 2007, Altland *et al.* 2008) documented that DFB (Douglas Fir Bark) alone provided sufficient micronutrients for annual vinca (*Catharanthus roseus* L.) grown at low pH (4.6-5.5). While Hernandez-Apaolaza *et al.* (2005) suggested that the use of pink bark in coconut (*Cocos nucifera* L.) coir-based media formulations served as one alternative of recycling waste materials. Fisher *et al.* (2006) suggested peat-based substrate pre-treated with lime with adjusted pH within an optimum range was physico-chemically very effective.

Coir dusts with a particle size distribution similar to peat showed comparatively higher aeration and lower capacity to hold total and easily available water. An air-water balance similar to that in peat became apparent in coir dust at a comparatively lower coarseness index (29% vs. 63% by weight in peat). Stepwise multiple regression analysis showed that particles with diameters in the range of 0.125 to 1 mm had a remarkable and highly significant impact on the physical properties, while particles < 0.125 mm and > 1 mm had only a slight or non-significant effect (Abad *et al.* 2005). Four types of media [coir, 1 coir: 2 peat (by volume), peat, and sandy loam soil] were evaluated by Merhaut and Newman (2005) for their effects on plant growth and nitrate (NO_3^-) leaching in the production of oriental lilies (*Lillium* L.) 'Starfighter' and 'Casa Blanca'. Results indicated that the use of coir and peat did not significantly influence plant growth (shoot dry weight) relative to the use of sandy loam soil. However, substrate type influenced the amount of NO_3^- leached through the media and N accumulation in the shoots for 'Starfighter', but not for 'Casa Blanca'. Various recipes for potting mixture have been developed (Kuepper and Adam 2003, Salifu *et al.* 2006).

NUTRIENT-MICROBE SYNERGY

In-vitro response

A rhizosphere-based microbe, if it is effective in triggering the plant growth, it should effectively utilise the nutrient as a source of energy for microbial proliferation. A strain of *Trichoderma harzianum* was tested *in vitro* for its compatibility with different concentrations of commonly used inorganic fertilizers. Four different inorganic fertilizers, viz. urea, single super phosphate (SSP), muriate of potash (MOP) and calcium ammonium nitrate (CAN) were used, each at concentrations of 100, 200, 500, 1000, and 2000 ppm. Urea at 1000 ppm and above increased the canopy diameter of *T. harzianum* by 11.1%. MOP increased the growth of the biological control agent at all concentrations tested while SSP and CAN both inhibited it. The inhibition ranged from 8.8% to 23% for SPP and from 11.1% to 71.9% for CAN and increased with the increase in concentration (Shylaja and Rao 2012). Response of different concentrations of all the seven commercially used fertilizers was observed statistically significant (Table 4). Interestingly

Table 4 Nutrient microbe interaction response (measured by colony growth in mm) under controlled conditions

Fertilizer Type	Fertilizer concentration (ppm)						CD (P=0.05)
	Control	100	200	400	800	1600	
	Colony growth (mm)						
Pseudomonas fluorescens							
Urea	14.0	20.5	30.5	21.6	22.0	16.0	1.41
KH_2PO_4	13.3	16.6	21.3	18.5	18.3	18.5	1.64
MOP	12.6	21.0	22.3	23.3	25.6	22.3	0.84
$FeSO_4$	14.6	21.5	20.3	16.0	16.0	16.2	0.94
$ZnSO_4$	16.3	24.0	19.0	20.6	19.0	17.5	1.10
Bacillus mycoides							
Urea	18.3	27.6	29.6	32.3	33.3	34.3	2.18
KH_2PO_4	33.0	35.3	36.0	34.6	32.6	38.6	1.10
MOP	29.0	23.6	30.6	32.3	33.6	31.6	0.80
$FeSO_4$	31.6	32.3	32.3	22.6	20.3	19.6	0.90
$ZnSO_4$	27.0	33.0	31.0	28.0	14.3		1.81
$MnSO_4$	29.3	29.6	17.5				NS

MOP stands for muriate of potash

Source: Srivastava *et al.* (2014a).

colony growth of *Pseduomonas fluorescens* and *Bacillus mycoides* were triggered by all the nutrients off course at varying concentrations much against our conventional notion that soil looses its biological dynamism owing to repeated and indiscriminate use of inorganic source of nutrients.

In-vivo response

In-vivo studies (Table 5) on the other hand, have revealed astonishing results exploiting the inorganic/nutrient-microbe synergy commercially to really unlock the possible productivity stagnation in fruit crops.

A review of long-term experiments conducted around the world indicated that chemical fertilizer alone is not enough to improve or maintain soil fertility at high levels and the soil acidification problem caused by over-application of synthetic N fertilizers can be reduced if more fertilizer N is applied as NO_3 relative to ammonium- or urea-based N fertilizers (Pathak and Nedwell 2011). Organic fertilizers can improve soil fertility and quality, but long-term application with high rates can also lead to more nitrate leaching, and accumulation of P, if not managed well. Well-managed combination of chemical and organic fertilizers can overcome the disadvantages of applying single source of fertilizers and substantially achieve higher crop yields, improve soil fertility, alleviate soil acidification problems and increase nutrient-use efficiency compared with only using chemical fertilizers (Miao *et al.* 2011).Organic amendments comprising manures have helped in increasing the fruit yield coupled with quality, effectively replacing mineral fertilizers in the nutrient management of commercial fruit tree orchards through associated changes in soil C pool, microbial pool and available nutrient pool of soil (Baldi *et al.* 2010, Montanaro *et al.* 2010, 2012).

Nutrient (nutrient as well as inorganic source)-microbe as tripartite association on the other hand is better known in fruit crops (Singh and Banik 2011, Srivastava 2009, 2012, Srivastava and Ngullie 2009, Khehra and Bal 2014) with respect to both agronomic response as well as soil health. An array of fruit crops have been reported to respond to the synergies originated through combination of organic nutrient-microbe-inorganics (Table 6). And such associations have invariably witnessed substantially higher productivity than any single component alone. However, there is a greater need to expand such plant response advantages using more rhizocompetent microbes preferably in consortium mode, plant response as well as soil health response both have to be sustained on a long term basis. Accrued long term field experiment data on evaluation of organic nutrient-microbe-inorganics popualry known as integrated nutrient management (INM) strategy in Nagpur mandarin (*Citrus reticulata* Blanco) carried out with the objective of working out an efficient INM module grown on Vertic Ustochrept showed much better effectiveness of microbial consortium (MC) when used in combination with inorganic fertilizers (IF) and organic manure (OM), farmyard manure (FYM) or vermicompost (Vm). However latter could produce much higher magnitude of response (Table 7). The net increase in canopy volume within four years (2007-12) with 100% recommended dose of fertilizers (RDF) was much higher compared with 75% RDF plus 25% Vm plus MC, with significantly better fruit quality parameters. Soil quality parameters in terms of soil microbial biomass (SMB) and soil microbial biomass nutrients (SMBN) were much lower with 75% RDF plus 25% Vm plus MC as compared with exclusive use of IF as 100% RDF. These changes within rhizosphere were very well translated into consequent improvements in leaf nutrient composition, being significantly higher with 75% RDF plus 25% Vm plus MC over 100% RDF. These observations warranted strong support in favour of INM-based treatments than sole use of IF (Srivastava *et al.* 2015). Such changes in soil management practices will play a significant ecological role in switching

Table 5 Response of nutrient-microbe synergy in different fruit crops

Crop	Type of nutrient-microbes involved	Response parameters	Reference
Banana (*Musa acuminata* L.)	*Azosprillum brasilense*- 100% RDF-based N	Leaf N content, chlorophyll content and bunch weight	Tiwari *et al.* (1999)
Banana (*Musa acuminata* L.)	*Azotobacter chroococcum*–80% RDF-based N	Plant height, number of leaves and shoots, and pseudo-stem diameter	Dibut-Alvarez *et al.* (1996)
Apple (*Malus domestica* Borkh.)	*Azotobacter chroococcum* – 80% RDF-based N	Fruit yield and leaf nutrient composition	El-Boray *et al.* (2006)
Mango (*Manifera indica* L.)	*Azotobacter chroococcum* – 48 g N/seedling	Plant height, seedling diameter and number of leaves	Kerni and Gupta (1986)
Banana (*Musa acuminata* L.)	*Azotobacter chroococcum* – 75% inorganic N	Total sugar, starch and protein	Sharma (2002)
Mosambi (*Citrus sinensis* Osbeck)	*Glomus fasciculatum* – 75% P_2O_5 + 25% N	Plant height, trunk diameter, canopy volume and biomass production	Singh *et al.* (2002)
Peach (*Prunus persica* (L.) Stokes)	*Azotobacter chroococcum* 75% N (as RDF)	Plant height, girth and number of leaves	Godara *et al.* (1995)

RDF stands for recommended doses of fertilizers

Table 6 Different components of integrated nutrient management recommended for different fruit crops

Crop	INM practices	Reference
Guava (*Psidium guajava* L.)	FYM 50 kg/plant – *Azotobacter sp* 50 g/plant - *Azospirillum* sp 50 g/plant – *Sesbania* sp as green manure	Ram and Rajput (2000)
Pomegranate (*Punica granatum* L.)	400 g N- 100 g P_2O_5 – 300 g K_2O /plant – FYM 20 kg/plant,	Ghosh *et al.* (2012)
Papaya (*Carica papaya* L.)	Vermicompost 20 kg/plant – rhizosphere culture 50 g/plant- 150 N – 200 P_2O_5 – 200 K_2O g/plant (75% RDF)	Kirad *et al.* (2010)
Banana (*Musa acuminata* L.)	FYM 12 kg/plant – *Azospirillum sp* 50 g/plant - Phosphate Solubilising Bacteria 50 g/plant *T.harzianum* 50 g/plant	Hazarika and Ansari (2010)
Banana (*Musa acuminata* L.)	50% RDF- FYM 20 kg/plant – *Azotobacter sp* 50 g/plant – Phosphate solubilising bacteria 50 g/plant –VAM 250 g/plant	Patil and Shinde (2013)
Guava (*Psidium guajava* L.)	488 g N – 244 g P_2O_5 - 281 g K_2O/plant – FYM 50 kg/plant – *Azotobacter* 250 g/plant – phosphate solubilising bacteria 25 g/plant	Barne *et al.* (2011)
Strawberry (*Fragaria ananassa* Duches)	75% N as RDF – 25% N as FYM – *Azotobacter* sp	Umer *et al.* (2009)
Pomegranate (*Punica granatum* L.)	300 g N/plant – neem cake 1 kg/plant	Ray *et al.* (2014)
Banana (*Musa acuminata* L.)	100% RDF – 40% Wellgrow organic manure	Kuttimani *et al.* (2013)
Peach (*Prunus persica* (L.) Stokes)	75% RDF - 25% N equivalent FYM	Shah *et al.* (2014)
Lemon (*Citrus limon* (L.) Burm.f.)	N 525 g/plant – FYM 150 kg/plant – *Azotobacter* sp 18 g/plant	Khehra and Bal (2014)
Apricot (*Prunus armeniaca* (L.))	75% RDF – 25% FYM	Shah *et al.* (2006)
Papaya (*Carica papaya* L.)	50% RDF (100 N – 100 P_2O_5 – 125 K_2O g/plant)- *Azotobacter* sp 50 g/plant – Phosphate solubilising bacteria 2.5 g/m^2	Singh and Varu (2013)
Guava (*Psidium guajava* L.)	50% RDF (250 g N – 100 g P_2O_5 - 250 K_2O g/plant) - FYM 25 kg/plant – vermicompost 5 kg/plant	Dwivedi (2013)
Sapota (*Achras zapota* L.)	75% RDF + 25% RDF equivalent vermicompost	Hebbarai *et al.* (2006)
Mango (*Mangifera indica* L.)	500 g N - 250 g P_2O_5 – 250 K_2O g/plant –50 kg FYM/plant – *Azospirillum* sp 250 g/plant	Singh and Banik (2011)
Mango (*Mangifera indica* L.)	250 N – 425 P_2O_5 – 1000 K_2O – *Azospirillum* sp 250 g/plant – PSB – 250 g/plant – $ZnSO_4$ 100 g/plant – Borax 100 g/plant	Hasan *et al.* (2012)
Banana (*Musa acuminata* L.)	100 % RDF – FYM 10 kg/plant – *Azospirillum* sp 25 g/plant Phosphate solubilising bacteria 250 g/plant	Bhalerao *et al.* (2009)
Guava (*Psidium guajava* L.)	236 g N – 66 g P_2O_5 – *Azospirillum* sp 30 g/plant – VAM 30 g/plant	Dutta *et al.* (2009)
Mosambi (*Citrus sinensis* Osbeck)	300 g N – 250 g P_2O_5 – 300 g K_2O – AMF 10 g/plant - *Azospirillum* sp 25 g/plant	Patel *et al.* (2009)
Guava (*Psidium guajava* L.)	250 g N – 100 g P – 250 g K_2O /plant – *Azotobacter* sp 250 g/plant	Shukla *et al.* (2009)
Litchi (*Litchi chinensis* Sonn.)	500 g N – 250 g P_2O_5 – 500 g K_2O /plant – FYM 50 kg/plant – *Azotobacter* sp 150 g/plant – VAM 100 g/plant	Dutta *et al.* (2010)
Aonla (*Emblica officinalis* Gaertn.)	50% NPKS (105 kg N – 7.20 kg P_2O_5 – 125.25 kg K_2O/ha) – Biofertilizers (*Azotobacter* sp – *Azospirillum* sp – Phosphate solubilising bacteria) – FYM (2 tonnes/ha)	Yadav *et al.* (2007)
Aonla (*Emblica officinalis* Gaertn.)	100 g N – 25 g P_2O_5 – 150 g K_2O/plant – FYM 10 kg/plant – Phosphate solubilising bacteria 50 g/plant	Mandal *et al.* (2013)
Sapota (*Achras zapota* L.)	1500 g N – 1000 P_2O_5 – 500 g K_2O/plant – 75 kg FYM – 12.5 g/plant PSB	Dalal *et al.* (2004)
Guava (*Psidium guajava* L.)	50% RDF (225 g N – 195 g P_2O_5 – 150 g K_2O/plant)- FYM 50 kg/plant – *Azospirillum* 250 g/plant	Goswami *et al.* (2012)

RDF and PSB stand for recommended doses of fertilizers and phosphate solubilising bacteria predominantly (*Pseudomonas fluorescens*), respectively

Table 7 Response of microbial consortium in integrated nutrient management module on fruit yield, quality and rhizosphere properties of Nagpur mandarin (2007-2013)

Treatment	Fruit yield* (kg/tree)	Fruit quality parameters (%)*			Rhizosphere properties					Carbon emission rate (mg C/m²/hr)
					SMB (cfu × 10³/g soil)		SMBN (mg/kg)			
		Juice	TSS	Acidity	BC	FC	C_{mic}	N_{mic}	P_{mic}	
T_1 (100% RDF)	15.6	46.4	9.2	0.78	32	16	152.1	19.1	16.1	
T_2 (75% RDF + MC)	8.4	47.2	8.9	0.78	31	16	146.3	19.3	15.2	
T_3 (75% RDF + 25% FYM)	9.2	47.8	9.3	0.70	45	19	159.1	23.9	15.9	
T_4 (50% RDF + 50% FYM)	9.8	46.9	9.4	0.71	44	20	164.1	25.6	17.0	
T_5 (75% RDF + 25% FYM + MC)	14.5	46.8	9.2	0.79	57	25	169.7	29.6	17.6	
T_6 (50% RDF + 50% FYM + MC)	12.8	46.9	9.4	0.80	48	26	169.2	30.3	19.3	
T_7 (75% RDF + 25% Vm)	34.8	47.2	9.3	0.74	50	25	169.6	29.2	18.9	6287.6
T_8 (50% RDF + 50% Vm)	38.9	48.4	9.6	0.70	53	26	176.1	29.8	20.4	2773.6
T_9 (75% RDF + 25% Vm + MC)	38.6	48.8	9.7	0.70	68	41	202.5	49.4	24.5	2584.9
T_{10} (75% RDF + Gm + MC)	11.2	47.2	9.2	0.74	50	25	178.6	31.8	18.6	2432.8
T_{11} (50% RDF + Gm + MC)	10.6	47.2	9.0	0.74	44	25	170.7	28.6	17.2	1396.4
CD (P=0.05)					3.7	2.2	2.6	1.9	3.0	

- MC stands for microbial consortium developed by isolating the native microbes from the experimental soil (mixture of *Azotobacter chrococcum*, *Bacillus mycoides*, *Bacillus polymyxa*, *Pseudomonas fluorescens* and *Trichoderma harzanium*). - FYM,Vm,Gm, and RDF stand for farmyard manure,vermicompost, green manuring, and recommended doses of fertilizers, (600 g N – 200 g P_2O_5 – 100 g K_2O/plant) respectively. - BC and FC stand for bacterial count and fungal count, respectively. - SMB and SMBN stand for soil microbial population and soil microbial biomass nutrients, respectively. * Fruit yield and fruit quality parameters represent initial 3 seasons only.

Source: Srivastava *et al.* (2014a)

the rhizosphere from C source to net C sink (Table 7). However, carbon economy at orchard scale is mainly driven by the capture versus emission trade-off . Soil CO_2 flux on the other hand is very heterogeneous, mainly due to spatial variability in soil structure, temperature, moisture, population density of bacteria and fungi and to the root density as well as to the concentration of organic matter in the soil (Yang *et al*. 2007). Such changes are also dictated by perennial fruit-based land use against the nature of reference land use, usually taken forest as standard land use (Bernardi *et al.* 2007).

RESEARCH AND DEVELOPMENT ISSUES

Despite many cutting edge technologies, addressing a variety of core issues on role of soil management-based nutrient use efficiency (Lipecki and Berbec 1997) in raising the productivity of perennial fruits is the major research and developmental issue. Microbes are most diverse soil organisms, yet very little is known about them. Until recently, research has focused on those organisms that are culturable. However a wealth of information is now being collected from both culturable and, as yet, unculturable organisms. Functions of the soil microbial population impact many processes and, therefore, productivity (Kennedy and Gewin 1997), if mechanisms involved in the plant-microbe interaction are better understood.

A plant manufactures microbial communities according to its metabolic requirements. The microbial biomass is one of the biological properties of soil that undergoes immediate change in response to fertilizer like input. Studies, therefore, need to be undertaken with a view to explore the possibility of which soil microbial property could be used as a potential tool for finding out soil health related constraint instead of concentration of available nutrients in soil using some indicator fruit crop(s). While the genetic, functional and metabolic diversity of soil microorganisms within the rhizosphere of wide range of fruit crops is important, the capacity of soil microbial communities to maintain functional diversity of those critical soil processes could ultimately be more important to ecosystem productivity and stability than mere taxonomic diversity (Caldwell 2005). In this context, it remains to be assessed how nutrient-microbe synergism is associated with productivity of perennial fruits. New research methods involving molecular techniques will extend our understanding of taxonomic and functional diversity in soil systems.

With the availability of more technical know-how on combined use of organic manures, prolonged shelf life of microbial bio-fertilizers, and inorganic chemical fertilizers, an understanding on nutrient acquisition and regulating the water relations would help switch orchards to CO_2 sink (expanding carbon capturing capacity of rhizosphere) so that a more sustainable fruit-based integrated crop production system under biotic and abiotic stress could be evolved. The molecular approach to breeding of mineral deficiency resistance and mineral efficiency would facilitate to produce nutritionally efficient biotypes in order to maximise the quality production of fruit crops on sustained basis. The work related to microbial inoculants for mass production, formulation coupled with innovative marketing, interaction and signalling with the plant and soil environment need further redressal to reorient fruit nutrition research.

Role of AMF in providing an additional resilience to rhizosphere's ability of carbon accredition within rhizosphere and associated development of plant's antioxidant profile as a defense mechanism (Wu *et al.* 2013) should divert the research studying strong mycorrhizal dependency of fruit crops. Rhizosphere specific AMF-based microbial consortium would add a new dimension in providing newer options for raising the productivity potential of fruit crops through an elevated plant rhizosphere health. Such microbial consortium could be effectively harmonised with fertigation as well to enhance fertilizer use efficiency. Of late, accruing responses on foliar spray of microbial consortium as biosurfacetant in combination of micronutrients needs to be tested besides their application scheduling in relation to crop phenology. Researches are using different approaches for screening rhizobacteria to select effective PGPR including promotion of root/shoot growth under genotobiotic conditions, *in*-vitro production of plant growth regulators/ biologically active substances and assessing of ACC-deaminase activity of the rhizobacteria (Zahir *et al.* 2003).

Perennial fruit trees act as strong carbon sink by sequestering the atmospheric carbon (Sugiura *et al*. 2007). Studies in the past have shown increase in yield of fruit crops like apple (Wu *et al.* 2012), grape (Bindi *et al.* 1997), Japanese pears (Ito *et al.* 1999), mango (Goodfellow *et al.* 1997), citrus (Peng *et al.* 2000) etc. in response to elevated CO_2 concentration. It remains to be investigated, how nutrient-microbe association could bring better dividends towards accurate estimation of orchard C budget vis-a-vis time scale and feedback mechanisms of changes in soil carbon pool and steady state level under specific fruit crop in order to expand potential of C credits through perennial fruit crops. Crop specific rhizosphere microbial properties in relation to climate variation would further open up newer challenges for modelling nutrient and microbial dynamics for improved nutrient use efficiency and increasing the knowledge on atmosphere–soil C fluxes mechanisms.

REFERENCES

Abad M, Fornes F, Carolina C, Noguera V, Noguera P, Maquieira A, and Puchades R. 2005. Physical properties on various coconut coir dusts compared to peat. *HortScience* **40**: 2 138–44.

Ahmed Feza M, Abhijit Samanta, and Abida Jabeen. 2010. Response of sweet cherry (*Prunus avium*) to fertigation of nitrogen, phosphorus and potassium under Kerawa land of Kashmir valley. *Indian Journal of Agricultural Science* **80**: 512–6.

Alagawadi A R and Gaur A C. 1992. Inoculation of *Azospirillium brasilense* and phosphate-solubilizing bacteria on yield of sorghum [*Sorghum bicolor* (L.) Moench] in dry land. *Tropropical Agriculture* **69**: 347–50.

Altintas S and Bal U. 2005. Application of *Trichoderma harzianum* increases yield in cucumber (*Cucumis sativus*) grown in an unheated glasshouse. *Journal of Applied Horticulture* **7**: 25–8.

Altintas S and Bal U. 2008. Effects of the commercial product based on *Trichoderma harzianum* on plant, bulb and yield characteristics of onion. *Science Horticulture* **116**: 219–22.

Altland J E. 2006. Substrate pH, a tricky topic. Digger **50**: 42–7.

Altland J E and Buamscha M G. 2008. Nutrient availability from Douglas Fir Bark in response to substrate pH. *Horticultural Science* **43**: 478–83.

Altland J E, Buamscha M G, and Horneck D A. 2008. Substrate pH affects nutrient availability in fertilized Douglas Fir Bark substrates. *Horticultural Science* **43**: 2 171–8.

Amor del F M, Serrano-Martinez A, Fortea M I, Legua P, and Nunez-Delicado E. 2008. The effect of plant-associative bacteria (*Azospirillum* and *Pantoea*) on the fruit quality of sweet pepper under limited nitrogen supply. *Science Horticulture* **117**: 191–6.

Arikan S, Ipek M and Pirlak L. 2013. Effect of plant growth promoting rhizobacteria (PGPR) on yield and fruit quality of Quince. IPCBEE 60: 97-06. (DOI: 10.7763/ IPCBEE.2013.V60.19).

Arora N K and Singh R. 2006. Effect of time of supplemental nitrogen application on canopy volume, flowering and yield of semi-soft pear cv. Punjab Beauty. *Indian Journal of Horticulture* **63**: 202–4.

Aseri G K, Jain N, Panwar J, Rao A V, and Meghwal P R. 2008. Biofertilizers improve plant growth, fruit yield, nutrition, metabolism and rhizosphere enzyme activities of pomegranate (*Punica granatum* L.) in Indian Thar desert. *Science Horticulture* **117**: 130–5.

Aseri G K, Rao A V, and Meghwal P R. 2005. Rhizosphere enzymes: an index to detect changes in the microbial functioning in soil around fruit plants as affected by bio-inoculants. *Indian Journal of Horticultural Science* **62**: 398–401.

Aslantas R, Cakmakci R and Sahin F. 2007. Effect of plant growth promoting rhizobacteria on young apple tree growth and fruit yield under orchard conditions. *Science Horticulture* **111**: 371–7.

Badiyala S D, Awasthi R P and Gupta R D. 1990. Effect of fertilisers and management practices on microflora in Alfiols growing citrus. *Journal of the Indian Society of Soil Science* **38**: 537–40.

Baker R, Elad Y and Sneh B. 1986. Physical, biological and host factors in iron competition in soils. *(In) Iron Siderophores, and Plant Diseases*, pp 77–84. Swinburne T R (Ed). Plenum Publishing Corporation, New York, USA.

Bal U and Altintas S. 2006a. A positive side effect from *Trichoderma harzianum* the biological control agent: increased yield in vegetable crops. *Journal of Environmental Protection and Ecology* **7**: 383–7.

Bal U and Altintas S. 2006b. Application of the antagonistic fungus *Trichoderma harzianum* (TrichoFlow WP™) to root zone increases yield of bell peppers grown in soil. *Biology Agriculture and Horticulture* **24**: 149–63.

Bal U and Altintas S. 2006c. Effects of *Trichoderma harzianum* on yield and fruit quality characteristics of tomato (*Lycopersicon esculentum* Mill.) grown in an unheated greenhouse. *Australian Journal of Experimental Agriculture* **46**: 131–6.

Bal U and Altintas S. 2008. Effects of *Trichoderma harzianum* on lettuce in protected cultivation. *Journal of Central European Agriculture* **9**: 63–70.

Baldi E, Toselli M, Marcolini G, Quartieri M, Cirillo E, Innocenti A and Marangoni B. 2010. Compost can successfully replace mineral fertilizers in the nutrient management of commercial peach orchard. *Soil Use and Management* **26**: 346–53.

Banyal S K and Sharma S K. 2011. Effect of fertigation and rootstock on yield and quality of apple. *Indian Journal of Horticulture* **68**: 419–24.

Barker W W and Banfield J F. 1998. Zones of chemical and physical interaction at interfaces between microbial communities and minerals. *Geomicrobiology* **15**: 223–44.

Barker W W, Welch S A and Banfield J F. 1997. Geomicrobiology of silicate minerals weathering. *Reviews in Mineralogy and Geochemistry* **35**: 391–428.

Barker W W, Welch S A, Chu S and Banfield F. 1998. Experimental observations of the effects of bacteria on alumino-silicate weathering. *American Mineralogist* **83**: 1 551–63.

Barne Varsha G, Bharad S G, Dod V N and Baviskar M N. 2011. Effect of integrated nutrient management on yield and quality of guava. *Asian Journal of Horticulture* **6**: 546–8.

Bashan Y. 1999. Interactions of *Azospirillum* spp. in soils: a review. *Biology and Fertility of Soils* **29**: 246–56.

Bashan Y and Holguin G. 1995. Inter-root movement of *Azospirillum brasilense* and subsequent root colonization of crop and weed seedlings growing in soil. *Microbial Ecology* **29**: 269–81.

Bashan Y and Holguin G. 1997. *Azospirillum*-plant relationships: environmental and physiological advances (1990-1996). *Canadian Journal of Microbiology* **43**: 103–21.

Bashan Y and Holguin G. 1998. Proposal for the division of rhizobacteria into two classifications: Biocontrol – PGPB (Plant growth promoting bacteria) and PGPB. *Soil Science and Biochemistry* **30**: 1 225–8.

Bashan Y, Holguin G and de-Bashan L E. 2004. *Azospirillum*-plant relationships: physiological, molecular, agricultural, and environmental advances (1997-2003). *Canadian Journal of Microbiology* **50**: 521–77.

Basu M, Mondal P, Basak R K, Basu T K and Mahapatra S C. 2006. Effect of cobalt, rhizobium and phosphobacterium inoculations on yield and nutrient uptake in summer groundnut (*Aachis hypogaea* L.) on alluvial soils. *Journal of Indian Society of Soil Science* **54**: 60–4.

Bavareco L and Fogher C. 1992. Effect of root infection with *Pseudomoas fluorescens* and *Glomus mossease* in improving Fe-efficiency of grapevine ungrafted rootstocks. *Vitis* **31**: 163–8.

Bavareco L and Fogher C. 1996a. Lime-induced chlorosis of grapevine as affected by rootstock and root infection with arbuscular mycorrhiza and *Pseudomonas fluorescens*. *Vitis* **35**: 119–23.

Bavareco L and Fogher C. 1996b. Effect of root infection with *Pseudomoas fluorescens* and *Glomus mossease* on severity of lime-induced chlorosis in *Vitis vinifera*, cv. ‘Pinot Blanc’. *Journal of Plant Nutrition* **19**: 1 319–29.

Baziramakenga R, Simard R R and Leroux G D. 1995. Determination of organic acids in soil extracts by ion chromatography. *Soil Biology and Biochemistry* **27**: 346–56.

Belimov A A, Kojemiakov A P and Chuvarliyeva C V. 1995. Interaction between barley and mixed cultures of nitrogen fixing and phosphate solubilizing bacteria. *Plant and Soil* **173**: 29–37.

Bellone C H and Bellone de S C. 1995. Morphogenesis of strawberry roots infected by *Azospirilium brasilense* and VA mycorrhiza. *North Atlantic Treaty Organisation, Advance Study Institute, Series G* (Ecological Science) **37**: 251–5.

Berg Gabriele 2009. Plant-microbe interactions promoting plant growth and health : perspectives for controlled use of microorganisms in agriculture. *Applied Microbiology and Biotechnology* **84**: 11–8.

Bernardi, Alberto Carlos de Campos, Pedro Luiz Oliveira de Almeida Machdo, Beata Emoke Madari, Silvio Roberto de Lucena Tavares, David Vilas Boas de Campos, and Lindbergue de Ara•újo Crisóstomo 2007. Carbon and nitrogen stocks of an Arenosol under irrigated fruit orchards in semiarid Brazil. *Scientia Agricola*(*Piracicaba, Braz)* 64: http://dx.doi.org/10.1590/S0103-90162007000200010

Bertrand H, Plassard C, Pinochet X, Toraine B, Normad P and Cleyet-Marel J C. 2000. Stimulation of the ionic transport system in *Brassica napus* by a plant growth-promoting rhizobacterium (*Achromobaceter* sp.). *Canadian Journal of Microbiology* **46**: 229–36.

Bhalerao N M, Patil N M, Badgujar C O and Patil D R. 2009. Studies on integrated nutrient management for tissue cultured Grand Naine banana. *Indian Journal of Agricultural Resesearch* **43**: 107–12.

Bhattacharya P. 2001. Biofertilizer supplementary nutritional resource in citrus. (*In*) *Citrus,* pp 201–9. Shyam Singh, Naqvi Samh (Eds). International Book Distributing Company, Lucknow, India.

Bhattacharya P and Jain R K. 2000. Phosphorus solubilising biofertilizers in the whirlpool of rock phosphate-Challenges and opportunities. *Fertilizer News* **45**: 45–52.

Bindi M, Fibbi L, Gozzini B, Orlandini S, Seghi L and Poni S. 1997. The effect of elevated CO_2 concentration on grapevine growth under field conditions. *Acta Horticulturae* **42**: 325–30.

Biswas H, Dev Narajan and Brij Lal Lakaria. 2012. Effect of integrated nutrient management on soil properties, performance of aonla (*Emblica officinais* Gaertn) based on agri-horti system in Bundelkhand region. *Indian Journal of Soil Conservation* **40**: 141–6.

Bjorkman T, Blanchard L M and Harman G E. 1998. Growth enhancement of shrunken-2 sweet corn by *Trichoderma harzianum* 1295-22. effect of environmental stress. *Journal of the American Society for Horticultural Science* **123**: 35–40.

Brauer V S, Stomp M and Huisman J. 2012. The nutrient-load hypothesis: patterns of resource limitation and community structure driven by competition for nutrients in light. *American Naturalist* **179**: 721–40.

Brenner K, You L and Arnold F H. 2008. Engineering microbial consortia : a new frontier in synthetic biology. *Trends in Biotechnolgy* **26**: 483–9.

Briones A and Raskin L. 2003. Diversity and dynamics of microbial communities in engineered environments and their implications for process stability. *Current Opinion in Biotechnology* **14**: 270–6.

Bronick C J and Lal R. 2005. Manuring and rotation effects on soil organic carbon concentration aggregate size fractions on two soils in northeastern Ohio, USA. *Soil Tillage Research* **81**: 239–52.

Brundrett M C. 2009. Mycorrhizal associations and other means of nutrition of vascular plants: understanding the global diversity of host plant by resolving conflicting information and developing reliable means of diagnosis. *Plant and Soil* **320**: 37–44.

Buamscha M G, Altland J E, Sullivan D M and Horneck D A. 2007. Micronutrient availability in fresh and aged Douglas fir bark. *HortScience* **42**: 152–6.

Bunemann E K, Schwenka, G D and Van Zwiten L. 2006. Impact of agricultural inputs on soil organisms – a review. *Australian Journal of Soil Research* **44**: 379–408.

Caldwell Bruce C. 2005. Enzyme activities as a component of soil diversity : A review. *Pedobiologia* **49**: 637–44.

Cassán F, Bottini R, Schneider G and Piccoli P. 2001. *Azospirillum brasilense* and *Azospirillum lipoferum* hydrolyze conjugates of GA_{20} and metabolize the resultant aglycones to GA_1 in seedlings of rice dwarf mutants. *Plant Physiology* **125**: 2 053–8.

Chaney R L. 1988. Metal speciation and interaction among elements affect trace element transfer in agricultural and environmental food chains. (*In*) *Metal Speciation: Theory, Analysis, and Application,* pp 319–60. Kramer J R and Allen H E (Eds). Lewis Publishers, Chelsa, Madison, USA.

Chauhan Neena and Chandel J S. 2008. Effect of fertigation on growth, yield, fruit quality and fertilizer use efficiency on kiwi fruit (*Actinidia deliciosa* Chev.). *Indian Journal of Agricultural Sciences* **78**: 389–93.

Chen Y, Jurkevitch E, Bar-Ness E and Hadar Y. 1994. Stability constants of Pseudobactin complexes with transition metals. *Soil Science Society of America Journal* **58**: 390–6.

Chen G S, Yang Y S, Xie J S, Li L and Gao R. 2004. Soil biological changes for a natural forest and two plantation in subtropical China. *Pedosphere* **14**: 297–304.

Cheng L, Dong S, Guak S and Fuchigami L H. 2001. Effects of nitrogen fertigation on reserve nitrogen and carbohydrate status and regrowth performance of pear nursery plants. *Acta Horticulturae* **564**: 51–62.

Chhonkar P K. 2003. Organic farming: Science and belief. *Journal of the Indian Society of Soil Science* **51**: 365–77.

Cornelis P. 2010. Iron uptake and metabolism in *Pseudomonas*. *Applied Microbiology and Biotechnology* **86**: 1 637–45.

Crespi B J. 2001. The evolution of social behaviour in microorganisms. *Trends in Ecology and Evolution* **16**: 178–83.

Dalal S R, Gonge V S, Jogdande N O and Moharia Anjali 2004. Response of different levels of nutrients and PSB on fruit yield and economics of sapota. *Panjabrao Deshmukh Krishi Vidyapeeth Research Journal* **28**: 126–8.

Dey P, Mathura Rai, Gangopadhyay K K, Biaksh Das, Vishal Nath and Reddy N. 2010. Effect of phosphorous on growth yield and nutrient use efficiency of litchi grown on Alfisol. *Indian Journal Horticulture* **67**: 394–5.

Dibut Alverz A, Rodriguez Nodals, Perez A. and Martinez Viera R. 1996. The effect of Azotoryzas double function on banana (*Musa* sp.) experimental condition. *Infomusa* **5**: 23–23.

Dobbelaere S, Croonenborghs A, Thys A, Ptacek D, Vanderleyden J, Dutto P, Labandera-Gonzalez C, Cabellero-Mellado J, Aguirrre J F, Kapulnik Y, Berner S, Burdman S, Kadour D, Sarig S and Okon Y. 2001. Responses of agronomically important crops to inoculation with *Azospirillum*. *Australian Journal of Plant Physiology* **28**: 871–9.

Dobbelaere S, Vanderleyden J and Okon Y. 2003. Plant growth promoting effects of diazotrophs in the rhizosphere. *Critical Reviews in Plant Sciences* **22**: 107–49.

Dubey A V, Vaishya U K, Bapat P N and Tomar V S. 1999. Phosphate solubilising efficiency of some microorganisms in Vertisol. *Journal of the Indian Soceity of Soil Science* **47**: 161–4.

Dubey S K and Gupta R K. 1996. Bio-organic fertilizers for improving productivity and legumes in Vertisols region of Madhya Pradesh. *Fertilizer News* **41**: 33–9.

Duffy B K and Défago G. 1999. Environmental factors modulating antibiotic and siderophone biosynthesis by *Pseudomonas fluorescens* biocontrol strains. *Applied Environmental Biotechnology* **65**: 2 429–48.

Dutt M, Patil P T and Sonawane, P C. 2002. Effect of various substrates on growth and flowering of chrysanthemum. *Indian Journal of Horticulture* **59**: 191–5.

Dutt M and Sonawane P C. 2006. Nutrient uptake in chrysanthemum grown on various substrates. *Indian Journal of Horticulture* **63**: 66–9.

Dutta P, Kundu S and Biswas S. 2010. Integrated nutrient management in litchi cv Bombai in new alluvial zone of West Bengal. *Indian Journal of Horticulture* **67**: 181–4.

Dutta P, Maji S B and Das B C. 2009. Studies on the response of bio-fertilizer on growth and productivity of guava. *Indian Journal of Horticulture* **66**: 39–42.

Duxbury J M, Borduzzaman M, Johnson S E, Lauren J G, Meisner C A and Welch, R M. 2006. Opportunities and constraints for addressing human mineral micronutrient malnutrition through soil management. *(In) Abstract 105:4.2B 18th World Congress of Soil Science* July 9-15, 2006, p 82, Philadelphia, Pennsylvania, USA.

Dwivedi Vandana 2013. Effect of integrated nutrient management on yield, quality and economics of guava. *Annal of Plant Soil Research* **15**: 149–51.

Eckert B, Weber O B, Kirchhof G, Halbritter A, Stoffels M and Hartmann A. 2001. *Azospirillium doebereinerae* sp., a nitrogen fixing bacterium associated with the C4-grass Miscanthus. *International Journal of Systematic and Evolutionary Microbiology* **51**: 17–26.

Elad Y, Chet I. and Henis Y. 2006. Biological control of *Rhizoctonia solani* in strawberry fields by*Trichoderma harzianum*. *Plant and Soil* **60**: 245–54.

El-Boray M S, Mostafa M F, Irage M A and Mohamed A A. 2006. Some recent trends of apple trees fertilization. *World Journal of Agricultural Sciences* **2**: 403–11.

El-Maksoud H K A, Boutros, B N and Lotfy A A. 1988. Growth response of sour orange, *Citrus aurantium* L. to mycorrhizal inocluation and superphosphate fertilization in sandy and calcareous soils. *Egyptian Journal of Soil Science* **28**: 385–95.

Elshanshoury A R. 1995. Interactions of *Azotobacter chroococcum*, *Azospirillum brasilense* and *Streptomyces mutabilis* in relation to their effect on wheat development. *Journal of Agronomy and Crop Science* **175**: 119–27.

Englander L. 1981. Rhododendron mycorrhizae. Brooklyn Botanic Garden Record. *Plants and Garden* **36**: 24–7.

Esitken A, Karlidag H, Ercisli S, Turan M and Sahin F. 2003. The effect of spray a growth promoting bacterium on the yield, growth and nutrient element composition of leaves of apricot (*Prunus armeniaca* L. cv. Hacihaliloglu). *Australian Journal of Agricultural Research* **54**: 377–80.

Esitken A, Pirlak L, Turan M and Sahin F. 2006. Effect of floral and foliar application of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrition of sweet cherry. *Scientia Horticulturae* **110**: 324–27.

Fabbrie P and Gallo Del M. 1995. Specific interaction between chickpea (*Cicer arietinum*) and three chickpea-*Rhizobium* strains inoculated singularly and in combination with *Azospirillum brasilense. North Atlantic Treaty Organisation, Advance Study Institute, Series G* (Ecological Science) **37**: 267–77.

Fageria N K, Baligar V C and Li Y C. 2008. The role of nutrient efficient plants in improving crop yields in the twenty first century. *Journal of Plant Nutrition* **31**: 1 121–57.

FAO. 2011. Statistical Year Book of Food and Agricultural Organization FAO State Div. Metalink: P3.Reu.FAO, ESS.FRD.AH Sci. p. 108-113. www.fao.org.docrep/017/i3138e/i3138e05.pdf.

Farooq M, Wahid A and Siddique K H M. 2012. Micronutrient application through seed treatments - a review. *Journal of Soil Science and Plant Nutrition* **12**: 125–42.

Ferguson J J. 1982. The use of mycorrhizae fungi in citrus. *Citrus Industry* **63**: 9–14.

Fernandez L, San Jose C, Cholette H and McKellar R C. 1988. Characterization of a pyoverdine-deficient mutant of *Pseudomonas fluorescens* impaired in the secretion of extracellular lipase. *Archives of Microbiology* **150**: 523–8.

Fisher P, Huang J and Argo W. 2006. Modeling lime reaction in peat-based substrates. *Acta Horticulturae* **718**: 461–8.

Gai J P, Cai X B, Feng G, Christie P and Li X L. 2006. Arbuscular mycorrhizal fungi associated with sedges on the Tibetan plateau. *Mycorrhiza* **16**: 151–7.

Gandotra V, Gupta R D and Bhardwaj K K R. 1998. Abundance of *Azotobacter* in great soil groups of northwest Himalayas. *Journal of the Indian Society of Soil Science* **46**: 379–83.

Gangata Varsha and Kaushal Rajesh 2009. Effect of plant growth promoting rhizobacteria (*Bacillus* species) on growth and nutrient uptake in cauliflower seedlings. *Annals of Plant Soil Research* **9**: 158–9.

Gaur A C. 1990. *Phosphate-Solubilising Microorganism as Biofertilizers*, pp 168–79. Omega Science Publishers, New Delhi.

Gaur A C and Gaind S. 1992. Role of phosphorus solubilising micro-organisms in crop productivity and enriched organic manure. *(In) Proceedings of the National Seminar on Organic Farming,* pp 134–42. Rai M R and Verma L N (Eds). Jawaharlal Nehru Krishi Vishwavidyalaya, Madhya Pradesh, India and Indira Gandhi Krishi Vishwavidyalaya, Chattisgarh, India.

Ghazi N A K. 2006. Nursery inoculation of tomato with arbuscular mycorrhizal fungi and subsequent performance under irrigation with sterile water. *Scientia Horticulturae* **109**: 1–7.

Ghosh S N, Bera B, Roy, S and Kundu A. 2012. Integrated nutrient management in pomegranate grown in laterite soil. *Indian Journal of Horticulture* **69**: 333–7.

Ghosh S N, Roy S N and Bora B. 2012. Nitrogen and potassium nutrition in sapota grown in lateriate soil. *Journal of Crop & Weed* **8**: 152–4.

Godara R K, Awasthi R P. and Kaith N S. 1995. Effect of biofertilizer and fertilizer on *Azotobacter* population, crown gall infection and alkaline phosphatase activity in peach. *Indian Journal of Plant Physiology* **38**: 334–6.

Godara R K, Awasthi R P and Kaith N S. 1996. Interaction effect of VA-mycorrhizae and *Azotobacter* inoculation on micronutrient content of peach seedlings. *Journal of Hill Research* **9**: 5–10.

Goodfellow J, Eamus D and Duff G. 1997. Diurnal and seasonal changes in the impact of CO_2 enrichment on assimilation, stomatal conductance and growth in long term study of *Mangifera indica* in the wet-dry tropics of Australia. *Tree Physiology* **17**: 291–9.

Gori A. and Favilli F. 1995. First results on individual and dual inoculation with *Azospirillum – Glomus* on wheat. *North Atlantic Treaty Organisation, Advance Study Institute, Series G* (Ecological Science) **37**: 245–9.

Goswami Amit Kumar, Lal Shant and Misra K K. 2012. Integrated nutrient management improves growth and leaf nutrient status of guava cv Pant Prabhat. *Indian Journal of Horticulture* **69**: 168–72.

Govindarajan K and Thangaraju M. 2001. *Azospirillum* – a potential inoculant for horticultural crops. *South Indian Horticulture* **49**: 233–5.

Graham J H. 1986. Citrus mycorrhizae: Potential benefits and interactions with pathogens. *HortScience* **21**: 1 302–06.

Graham J H and Fardelmann D. 1986. Inoculation of citrus with root fragments containing chlamydospores of the mycorrhizal fungus *Glomus intraradices*. *Canadian Journal of Botany* **64**: 1 739–44.

Graham J H and Timmer L. 1985. Rock phosphate as a source of phosphorus for vesicular-arbusuclar mycorrhizal development and growth of citrus in a soilless medium. *Journal of American Society of Horticulture Science* **110**: 489–92.

Guimarães V Danielle, Maria I S and Gonzaga, José de O. Melo Neto. 2014. Management of soil organic matter and carbon storage in tropical fruit crops. *Revista Brasileira de Engenharia Agrícola e Ambiental* **18**: 301–6.

Gyaneshwar P, Kumar G N, Parekh L J and Poole P S. 2002. Role of soil microorganisms in improving P nutrition of plants. *Plant and Soil* **245**: 83–93.

Handelsman J, Rondon M R, Brady S F, Clardy J and Goodman R M. 1998. Molecular biolgoical access to the chemistry of unknown soil microbes: a new frontier for natural products. *Chemistry and Biology* **5**: R245–R49.

Haneef Mohd, Kaushik R A, Sarolia D K, Mordia A and Mahesh Dhakar 2014. Irrigation scheduling and fergitaion in pomegranate cv Bhagwa under high density planting system. *Indian Journal of Horticulture* **71**: 45–8.

Hasan M A, Manna M, Dutta P, Bhattacharya K, Mandal S, Banerjee H, Ray S K and Jha S. 2012. Integrated nutrient management in improving fruit quality of Mango ‘Himsagar’. IX International Mango Symposium, ISHS *Acta Horticulturae* **992**.

Hassouma M G, Hassan M T and Madkour M A. 1994. Increased yield of alfalfa (*Medicago sativa*) inoculated with N_2-fixing bacteria and cultivated in a calcareous soil of Northwestern Egypt. *Arid Soil Research and Rehabilitation* **8**: 389–93.

Hazarika B N and Ansari S. 2007. Biofertilizers in fruit crops - A review. *Agricultural Reviews* **28**: 69–74.

Hazarika B N and Ansari S. 2010. Effect of integrated nutrient management on growth and yield of banana cv. Jahaji. *Indian Journal of Horticulture* **67**: 270–3.

Hazen T C, Jimenez L and Victoria G L. 1991. Comparison of bacteria from deep subsurface sediment and adjustment groundwater. *Microbiology and Ecology* **22**: 293–304.

Hebbarai M, Ganiger V M, Masthana Reddy B G and Joshi V R. 2006. Integrated nutrient management in sapota (*Manikara zapota*) using vermicompost to increase yield and quality. *Indian Journal of Agricultural Sciences* **76**: 587–90.

Herman M A B, Nault B A and Smart C D. 2008. Effects of plant growth promoting rhizobacteria on bell pepper production and green peach aphid infestations in New York. *Crop Protection* **27**: 996–1 002.

Hernandez -Apaolaza L, Gasco A M, Gasco J M and Guerrero F. 2005. Reuse of waste materials a growing media. *Communications in Soil Science and Plant Analysis* **24**: 349–63.

Holm P E, Nielsen P H, Albrechtsen H J and Christensen T A. 1992. Importance of unattached bacteria and bacteria attached to sediment in determining potentials for the degradation of xenobiotic organic contaminants in an aerobic aquifer. *Applied Environmental Microbiology* **58**: 3 020–6.

Huber D M and McCay-Buis T S. 1993. A multiple component analysis of the take-all disease of cereals. *Plant Disease* **77**: 437–47.

Huang Yong-Ming, Srivastava A K, Ying-NingZou, Qiu-DanNi, YuHan and Qiang-ShengWu 2014. Mycorrhizal-induced calmodulin mediated changes in antioxidant enzymes and growth response of drought-stressed trifoliate orange. *Frontiers in Microbiology* **5**: 682–8.

Huchche A D, Dass H C, Lallan Ram, Srivastava A K and Kohli R R.1996. Response of acid lime (*Citrus aurantifolia* Linn.) to nitrogen fertilisation. *Indian Journal of Horticulture* **53**: 14–8.

Irget M E, Aksoy U, Okur B, Ongun A R and Tepecik, M. 2008. Effect of calcium based fertilization on dried fig (*Ficus carica* L. cv Sarilop) yield and quality. *Scientia Horticulturae* **118**: 303–13.

Ito J, Hasegawa S, Fujita K, Ogasawara S and Fujiwara T. 1999. Effect of CO_2 enrichment on fruit growth and quality in Japanese pear (*Pyrus serotina* Reheder cv Kousui). *Journal of Soil Science and Plant Nutrition* **45**: 385–93.

Jasrotia A, Singh R P, Singh J M and Bhutani V P. 1999. Response of olive trees to varying levels of N and K fertilizers. *Acta Horticulturae* **474**: 337–9.

Jeeva S, Kulasekaran M, Shanmugavelu K G and Oblisami G. 1988. Effect of *Azospirillum* on growth and development of banana cv. Poovan (AAB). *South Indian Horticulture* **36**: 1–4.

Jeyakumar P, Amutha R, Balamohan T N, Auxcillia J and Nalina L. 2010. Fertigation improve fruit yield and quality of papaya. *Acta Horticulturae* **851**: 369–73.

Johnson C R. 1984. Phosphorus nutrition on mycorrhizal colonization, photosynthesis, growth and nutrient composition of *Citrus aurantium*. *Plant and Soil* **80**: 35–42.

Johnston A M, Khurana H S, Majumdar, K and Satyanarayana T. 2009. Site specific nutrient management – Concept, current research and future challenges in Indian agriculture. *Journal of the Indian Society of Soil Science* **57**: 1–10.

Joshi K C and Singh H P. 1995. Interrelation ship among vescicular arbuscular mycorrhize population, soil properties and root colonization capacity of soil. *Journal of the Indian Society of Soil Science* **43**: 204–7.

Karlidag H, Esitken A, Turan M and Sahin F. 2007. Effect of root inoculation of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrient element contents of leaves of apple. *Scientia Horticulturae* **114**: 16–20.

Keditsu R and Srivastava A K. 2014. Substrate dynamics : Developments and issues. *Annals of Plant and Soil Research* **16**(1): 1–8.

Kennedy Ann C and Gewin Virginia L. 1997. Soil microbial diversity : present and future considerations. *Soil Science* **162**: 607–17.

Kerni P N and Anil Gupta 1986. Growth parameters affected by azotobacterization of mango seedlings in comparison to different nitrogen doses. *Research and Development Reporter* **3**: 77–9.

Khan K Mohd, Mishra P K, Taru Sharma, Verma S K, Pragati Misra and Ramteke P W 2009. Screening of microbial strains for succinic acid production. *Annals of Plant and Soil Research* **11**: 67–8.

Khanam D. 2007. Assessment of arbuscular mycorrhizal association in some fruit plants in Bangladesh. *Bangladesh Journal of Microbiology* **24**: 34–7

Khandelwal Rohit, Choudhary S K, Jitendra Ghoshlya and Singh P. 2013. Effect of fertilizer and bio-fertilizer on growth, yield and economics of cowpea. *Annals of Plant and Soil Research* **15**: 177–8.

Khanizadeh S, Hamel C, Kianmehr H, Buszard D and Smith D L. 1995. Effect of three arbuscular mycorrhizal fungus species and phosphorus on productivity and vegetative growth of three strawberry cultivars. *Journal of Plant Nutrition* **18**: 1 073–9.

Khehra Savreet and Bal J S. 2014. Influence of organic and inorganic nutrient sources on growth of lemon (*Citrus limon* (L.) Burm.) cv Baramasi. *Journal of Experimental Biology Agricultural Sciences* **2**: 126–9.

Khot A B, Ashoka P, Neelkanth J K, Rajkumar S and Gundlur S S. 2012. Performance of early growth period of sapota (*Achras sapota* L.) to drip method of irrigation and fertigation of Vertisol. *Environment and Ecology* **30**: 1 513–6.

Kim H J, Boedicker J Q, Choi J W and Ismagilov R F. 2008. Defined spatial structure stabilizes a synthetic multispecies bacterial community. *Proceedings of the National Academy of Science,* USA **105**: 18 188–93.

Kirad K S, Barche S and Singh D B. 2010. Integrated nutrient management in papaya cv. Surya. *Acta Horticulturae* **1**: 377–80.

Klitgord N and Segré D. 2011. Ecosystems biology of microbial metabolism. *Current Opinion in Biotechnology* **22**: 541–6.

Kloepper J K, Leong J, Teintze, M and Schorth M N. 1980. Enhanced plant growth by siderphores produced by plant growth promoting rhizobacteria. *Nature* **28**: 885–6.

Kloepper J W, Lifshitz R and Zablotowciz R M. 1989. Free living bacterial inocula for enhancing crop productivity. *Trends in Biotechnology* **7**: 39–43.

Kohler J, Caravaca F, Carrasco L and Rolden A. 2007. Interaction between a plant growth-promoting rihzobacterium, an AM fungus and phosphate-solubilizing fungs in the rhizosphere of *Lactuca sativa*. *Applied Soil Ecology* **35**: 480–7.

Koster M, Ovaa W, Bitter, W and Weisbeek P. 1995. Multiple outer membrane receptors foruptake of Perric pseudobactins in *Pseudomonas putida* WCS358. *Molecular Genetics and Genomics* **248**: 735–43.

Krugger J A, Britz K, Tolmay C D and Du Plessis S F. 2000. Evaluation of an open hydroponic system (OHS) for citrus in South Africa: Preliminary Results. *(In) Proceedings of the International Society of Citriculture*, Vol 2, pp 239–42.

Krzyszowska A J, Blaylock M J, Vance G F and David M B. 1996. Iron chromatography analysis of low molecular weight organic acids in spodosol forest floor solutions. *Soil Science Soceity of America Journal* **60**: 1 565–71.

Kucey R M N. 1983. Phosphate-solubilizing bacteria and fungi in various cultivated and virgin alberta soils. *Canadian Journal of Soil Science* **63**: 671.

Kuepper G and Adam K. 2003. Organic potting mixes for certified production. Horticulture. (*In*) Horticulture Technical Note No. 112, Appropriate Technology Transfer for Rural Areas. National Sustainable Agriculture Information Service, Fyetteville, Arkansas, USA, pp 48–52.

Kuttimani R, Velayudham Somasundram E and Muthukrishnan P. 2013. Effect of integrated nutrient management on yield and economics of banana. *Global Journal of Biology, Agriculture and Health Sciences* **2**: 191–5.

Lal G, Pareek C S, Sen J L and Soni A K. 2003. Effect of N, P and K on growth, yield and quality of ber cv Umran. *Indian Journal of Horticulture* **60**: 158–62.

Lakso, Alan L. 2010. Esimating the environmental footprint of

New York apple orchards. *New York Fruit Quareterly* **18**: 26–8.

Lehoczky E, Debreczeni K and Szalai T. 2005. Available micronutrient contents of soils in long-term fertilization experiments in Hungary. *Communications in Soil Science and Plant Analysis* **36**: 423–30.

Lin S Y, Young C C, Hupfer H, Siering C, Arun, A B, Chen W M, Lai W A, Shen F T, Rekha P D and Yassin A F 2009. *Azospirillum picis* sp., isolated from discarded tar. *International Journal of Systematic and Evolutionary Microbiology* **59**: 761–5.

Lipecki J and Berbeæ S. 1997. Soil management in perennial crops : orchards and hop gardens. *Soil Tillage Research* **43**: 169–84.

Liu Chun-Yan, Srivastava A K and Qiang-Sheng Wu 2014. Effect of auxin inhibitor and AMF inoculation on growth and root morphology of trifoliate orange (*Poncirus trifoliata*) seedling. *Indian Journal of Agricultural Sciences* **84**(11): 1 342–6.

Lobell D B, Field C B, Chahill K N and Bonfils C. 2005. Impacts of future climate changes on California perennial crop yields : Model projections with climate and crop uncertainties. *Agricultural and Forest Meteorology* **141**: 208–18.

Loper J E and Henkels M D. 1999. Utlilzation of heterologous siderophores enhances levels of iron available to *Pseudomonas putida* and the rhizosphere. *Applied Environmental Microbiology* **4**: 5–13.

Loper J E and Schroth Y M 1986. Importance of sidephores in microbial interactions in the rhizosphere. *(In) Iron, Sidephores and Plant Diseases*, pp 85–9. Swinburne, T R (Ed). Plenum Publishing Company, New York, USA.

Lotka A J. 1992. Contribution to the energetic of evolution. *Proceedings of the National Acadent of Science* USA. **8**: 147–51.

Magalhães F M, Baldani J I, Santo J, Kuykendall J R and Dobereiner J. 1983. A new acid tolerant *Azospirillum* sp. *Annual Academy of Brazilian Cliêncology* **55**: 417–30

Mahmoud H M and Mahmoud F A F. 1999. Studies on effect of some biofertilizers on growth of peach seedlings and root rot disease incidence. *Egyptian Journal of Horticulture* **26**: 7–18.

Maity A, Jadhav V T and Ram Chandra 2012. Exploration of microbial wealth for sustainable horticultural production. *International Journal of Bio-resource and Stress Management* **3**: 489–500.

Mandal K K, Rajak A , Debnath S and Hasan M A. 2013. Integrated nutrient management in Aonla cv A-7 in the red lateritic region of West Bengal. *Journal of Crop and Weed* **9**: 121–3.

Manna M C, Swarup A, Wanjari R H, Singh Y V, Ghosh P K, Singh K N, Tripathi A K and Saha M N. 2005. Soil organic matter in a West Bengal Inceptisol after 30 years of multiple cropping and fertilization. *Soil Science Society of America Journal* **70**: 121–9.

Marschner P, Crowley D and Yang C H. 2004. Development of specific rhizosphere bacterial communities in relation to plants species, nutrition and soil type. *Plant and Soil* **261**: 199–208.

Martinez-Valero R and Fernandez C. 2004. Preliminary results in citrus groves grown under MOHT system. (*In*) *Proceedings of International Society of Citriculture,* Vol 1, p 103.

Mehnaz S, Weselowski B and Lazarovits G. 2007a. *Azospirillium canadense* sp., a nitrogen fixing bacterium isolated from corn rhizosphere. *International Journal of Systematic Evolutionary Microbiology* **57**: 620–4.

Mehnaz S, Weselowski B and Lazarovits G. 2007b. *Azopirillum zeae* sp., a diazotrophic bacterium isolated from rhizosphere soil of *Zea mays*. *International Journal of Systematic and Evolutionary Microbiology* **57**: 2 805–9.

Meldrum A J. 1999. Regulation of pyoverdine biosynthesis in *Pseudomonas aeruginosa.* M Sc Thesis, Queen's University, Kingston.

Mengel K and Kirkby E A. 2000. *Principles of Plant Nutrition*, pp 169–72. Kluwer Academic Publishers, London, UK.

Merckx R, Dijkstra A, Hartog A and Den Van Veen J A. 1987. Production of root derived material and associated microbial growth in soil at different nutrient levels. *Biology and Fertility of Soils* **5**: 126–32.

Merhaut D and Newman J. 2005. Effects of substrate type on plant growth and nitrate leaching in cut flower production on Oriental Lily. *HortScience* **40**: 2 135–7.

Miao Yuxin, Bobby A Stewart and Fusuo Zhang 2011. Long-term experiments for sustainable nutrient management in China. A reveiew. *Agronomy for Sustainable Development* **31**: 397–14.

Mir Muzaffar and Sharma Som Dev. 2012. Influence of biofertilizers on plant growth, fruit yield, nutrition and rhizosphere microbial activity of pomegranate (*Puica granatum* L.) cv. Kandhari Kasali. *Journal of Applied Horticulture* **14**: 129–36.

Mishustin E N, Sinironova, G.A and Lokmacheva R R. 1981. The decomposition of silicates by microorganisms and the use of silicate bacteria as bacterial fertilizers. *Biological Bulletin* **8**: 400–9.

Modaihsha S. 1997. Foliar application of chelated and non-chelated metals for supplying micronutrients to wheat grown on calcareous soil. *Experimental Agriculture* **33**: 237–45.

Molla A H, Shamsuddin Z H and Saud H M. 2001. Mechanism of root growth and promotion of nodulation in vegetable soybean by *Azospirillum brasilense*. *Communications in Soil Science and Plant Analysis* **32**: 2 177–87.

Montanaro G, Celano G, Dicho B and Xiloyannis C. 2010. Effects of soil-protecting agricultural practices on soil organic carbon and productivity in fruit tree orchards. *Land Degradation and Development* **21**: 132–8.

Montanaro G, Dicho B, Briccoli Bati C and Xiloyannis C. 2012. Soil management affects carbon dynamics and yield in a Mediterranean peach orchard. *Agriculture Ecosytems and Environment* **161**: 46–54.

Mostafa E A M, Sakeg M M S and El-Migeed Abd M M M. 2007. Response of banana plants to soil and foliar applications of magnesium. *American-Eurasian Journal of Agricultural and Environmental Sciences* **2**: 141–6.

Munir Muhammad, Baloch Jalal-ud-Din, Alizai, Atiq Ahmed and Ahmad Zia. 1992. Resposne of date palm cultivar Dhakki to NPK fertilizers. *Paksitan Journal of Agricultural Research* **13**: 347–9.

Mwamba Bwalya Jackson. 2013. Estimation of net carbon sequestration potential of citrus under different management systems using the life cycle approach. Research Thesis, University of Zambia Research Repository Online. http://dspace.unza.zm:8080/xmlui/handle/123456789/2202

Nair P R K. 1984. Soil productivity aspects of agro-forestry. International Council for Research in Agro-forestry, Nairobi, Kenya, pp 21–8.

Neilands J B. 1983. Siderphores. (*In*) *Iron Binding Proteins Without Cofactor or Sulfur Clusters*, pp 137–66. Theil E C, Eichhorn G L and Marzilli L G (Eds). Elsevier, New York, USA.

Neilsen D, Millard P, Neilsen G H, Hogue E J, Parchomchuck P and Zebarth B J. 2001. Remobilization and uptake of N by newly planted apple (*Malus domestica*) trees in response to irrigation method and timing of N application. *Tree Physiology* **21**: 513–21.

Nemec S. 1979. Response of six citrus rootstocks to three species of *Glomus*, a mycorrhiza fungus. *Citrus Industry* **5**: 5–14.

Neslson K H and Stahl D H. 1997. Microorganisms and biogeochemical cycles: what can we learn from stratified communities. *Reviews in Mineralogy and Geochemistry* **35**: 5–34.

Neto C, Carranca C, Clemente J and Varennes de A. 2008. Nitrogen distribution, remobilization and re-cycling in young orchard of non-bearing 'Rocha' pear trees. *Scientia Horticulturae* **118**: 299–307.

Neyra C A, Atkinson A and Olubayi O. 1995. Coaggregation of *Azospirillum* with other bacteria: basis for functional diversity. *North Atlantic Treaty Organisation, Adavance Study Institute, Series G* (Ecological Science) **37**: 429–39.

Okon Y. 1985. *Azospirillum* as a potential inoculant for agriculture. *Trends in Biotechnology* **3**: 223–8.

Okon Y and Labandera-Gonzalez C A. 1994. Agronomic applications of *Azospirillum*: An evaluation of 20 years worldwide field inoculation. *Soil Biology and Biochemistry* **26**: 1 591–601.

Onkarayya H and Sukhada M. 1993. Studies on dependency of citrus rootstocks to VAM inoculation in Alfisol Soil. *Advances in Horticulture Forestry* **3**: 81–91.

Orhan E, Ercisli E S, Turan M and Sahin F. 2006. Effects of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrient contents in organically grown rasberry. *Scientia Horticulturae* **111**: 38–43.

O'Sullivan D J and O'Gara F. 1992. Traits in fluorescent *Pseudomonas* spp. involved in suppression of plant root patheogens. *Microbiology Reviews* **56**: 662–76.

Padma T M R and Kandasamy D. 1990. Effect of interaction between VA-mycorrhizae and graded levels of phosphorous on the growth of papaya (*Carica papaya*). (*In*) *Proceedings of the National Conference on Trends in Mycorrhizal Research,* 14-16 February, Haryana Agricultural University, Hisar, Haryana India, pp 133–4.

Panda N. 1990. Agro-economic efficiency and rock phosphate in acid soils. *Fertilizer News* **35**: 47–8.

Paris F, Botton B and Lapeyrie F. 1996. *In vitro* weathering of phlogopite by ectoycorrhizal fungi. *Plant and Soil* **179**: 141–50.

Parker D R, Norvell W A and Chaney R L. 1995. GEOCHEM-PC: A chemical speciation program for IBM and compatible personal computers. *(In) Chemical Equilibrium and Reaction Models*, pp 253–69. Loeppert R H, Schwab A P and Goldberg S (Eds). Soil Science Society of America Special Publication, Soil Science Society of America, American Society of Agronomy, Madison, Wisconsin USA.

Patel V B, Singh S K, Asrey Ram, Nain Lata, Singh A K and Singh Laxman. 2009. Microbial and inorganic fertilizers application influenced vegetative growth, yield, leaf nutrient status and soil microbial biomass in sweet orange cv Mosambi. *Indian Journal of Horticulture* **66**: 163–8.

Pathak, H and Nedwell D B. 2011. Nitrous oxide emission from soil with different fertilizer, water levels and nitrification inhibitors. *Water, Air Soil Pollution* **129**: 217–28.

Pathak P K and Mitra S K. 2008. Effect of phosphorus, potassium, sulphur and boron on litchi. *Indian Journal of Horticulture* **65**: 137–40.

Patil D R, Sulikeri G S, Patil H B and Balikar R A. 2008. Studies on integrated nutrient management in Thompson seedless grapes. *Acta Horticulturae* 785.

Patil V K and Shinde B N. 2013. Studies on integrated nutrient management on growth and yield of banana cv Ardhapuri (Musa AAA). *Journal of Horticulture and Forestery* **5**(9): 130–8.

Pawar D D and Dingre S K. 2013. Influence of fertigation scheduling through drip on growth and yield of banana in western Maharashtra. *Indian Journal of Horticulture* **70**: 200–5.

Peng G, Wang H, Zhang G, Hou W, Liu Y, Wang E T and Tan Z. 2006. *Azospirillum melinis*, a group of diazotrophs isolated from tropical molasses grass. *International Journal of Systematic Evolutionary Microbiology* **56**: 1 263–71.

Peng L, Wang C, He S, Guo C and Yan C. 2000. Effects of elevation and climatic factors on the fruit quality of Navel orange. *South China Fruits* **29**: 3–4.

Pirlak L, Turan M, Sahin F and Esitken A. 2007. Floral and foliar application of plant growth promoting rhizobacteria (PGPR) to apples increases yield, growth and nutrient element contents of leaves. *Journal of Sustainable Agriculture* **30**: 145–55.

Poldma P, Merivee A, Johansson P, Ascard J and Alsanius B. 2001. Influence of biological control of fungal diseases with *Trichoderma spp.* on yield and quality of onion. (*In*) *New Sights in Vegetable Production,* pp 48–52. Nordic Association of Agricultural Scientists, Norway Serial no. 329, Segadi, Estonia.

Powlson D D. 1994. The soil microbial biomass: Before, beyond and back. (*In*) *Beyond the biomass, British Society of Soil Science,* pp 3–20. Ritz K, Dighton J and Giller K E (Eds). Wiley Sayee, London, UK.

Powlson D D, Brooks P C and Christen B T. 1987. Measurement of soil microbial biomass provides an early indication of changes in total organic matter due to straw incorporation. *Soil Biology and Biochemistry* **19**: 159–64.

Quiroga-Rojas L I, Ruiz-Quinones N, Munoz-Motta G and Lozano-Tovar M D. 2012. Rhizosphere microorganism, potential antagonists of *Fusarium* sp. causing agent of root rot in passion fruit (*Passiflora edulis* Sims). *Acta Agronomica* **61**: 244–50.

Ram R A and Rajput M S. 2000. Role of biofertilizers and manures on production of guava (*Psidium guajava* L.) cv. Allahabad Safeda. *Haryana Journal of Horticulture Science* **29**: 193–4.

Raman J. 2012. Response of *Azotobacter*, *Pseudomonas* and *Trichoderma* on growth of apple seedling. *International Proceedings of Chemical, Biological and Enironmental Engineering* **40**: 3–90.

Ramniwas Kaushik R A, Sarolia D K, Pareek Sunil and Sunil V. 2012. Effect of irrigation and fertigation scheduling on growth and yield of guava (*Psidium guajava* L.) under meadow orcharding. *African Journal of Agricultural Research* **7**: 6 350–6.

Rao A V and Dass H C. 1989. Growth of fruit plants as influenced by nitrogen fixing bacteria. *Annals of Arid Zone* **28**: 142–7.

Ray Dutta S K, Takawale P V, Chatterjee R and Hnamte V. 2014. Yield and quality of pomegranate as influenced by organic and inorganic nutrients. *Bioscan* **9**: 317–20.

Reddy B M C, Srinivas K, Padma P and Raghupati. 2002. Response of Robusta banana to N and K fertigation. *Indian Journal of Horticulture* **59**: 342–8.

Reídel E J, Brown P H, Duncu R A, Heerema R J and Weinbaum S A. 2004. Sensitivity of yield determinants to potassium deficiency in 'Nonpareil' almond. *Journal of Horticultural Science and Biotechnology* **79**: 906–10.

Rengel Z, Gutteridge R, Hirsch, P and Hornby D. 1996. Plant genotype, micronutrient fertilization and take-all infection influence bacterial populations in the rhizosphere of wheat. *Plant and Soil* **183**: 269–77.

Ribaudo C M, Rondanni D P, Cura J A and Fraschia A A. 2001. Response of *Zea mays* to the inoculation with *Azospirillum* on nitrogen metabolism under greenhouse conditions. *Plant and Biology* **44**: 631–4.

Roger T K. 1991. Nutrient supply, nutrient demand and plant response to mycorrhizal inoclulation in unsterile soil. *New Phytology* **117**: 365–86.

Rogers J R, Bennett P C and Choi W I. 1998. Feldspar as a source of nutrients for microorganisms. *American Minerals* **83**: 1 532–40.

Roose R and Haase D L. 2000. The use of coir as a containerized growing medium for Douglas fir seedlings. *Native Plants Journal* **1**: 107–11.

Rosche B, Li X Z, Hauer B, Schmid A and Beuhler K. 2009. Microbial biofilms : a concept for industrial catalysis ? *Trends in Biotechnology* **27**: 636–43.

Salifu F K, Nicodemus M A, Jacobs D F and Davis A S. 2006. Evaluating chemical indices of growing media for nursery production of *Quercus rubra* seedlings. *HortScience* **41**: 1 342–6.

Sankar V, Veragagavathatham D and Kannan M. 2009. Organic farming practices in white onion (*Allium cepa* L.). *Journal of Ecofriendly Agriculture* **4**: 17–21.

Sarangthem Indira, Sharma L Devarishi and Srivastava A K. 2014. Development of nutrient diagnostic technique for Khasi mandarin (*Citrus reticulata* Blanco) Grown in Manipur. *Journal of Indian Society of Soil Science* **62**(2): 118–25.

Scheludko A V, Krill V M, Tugarova A V, Krestinenko V A, Panasenko V I, Antonyuk L P and Katsy E I. 2009. Changes in motility of the rhziobacterium *Azospirillum brasilense* in the presence of plant lectins. *Microbiological Research* **164**: 149–56.

Sciubba E. 2011. What did Lotka really say? A critical reassessment of the "maximum" power principle". *Ecological Modelling* **222**: 1 347–53.

Shah Azam S, Mohammad W, Shah Mahmood S, Elahi Rizwan, Ali, Azaz Abdul Basir Haroon. 2014. Integrated effect of organic and inorganic nitrogen on peach fruit yield and orchard fertility. *Agricultural Science Research Journal* **4**: 78–82.

Shah Mahmood S, Mohammad Wisal Shah, Azam S and Nawaz Haq 2006. Integrated nitrogen management of young deciduous apricot orchard. *Soil and Environment* **25**: 59–63.

Shamseldin A, El-Sheikh Mohamad H, Hassan H S A and Kabeil S S. 2010. Microbial biofertilization approaches to improve yield and quality of Washington navel orange and reducing the survival of nematode in the soil. *Journal of American Science* **6**: 264–71.

Sharma R. 2002. Effect of nitrogen sources on growth, yield and quantity of banana cv. Barjahaji (Musa AAA group, Cavendish Subgroup). Ph D Thesis, Assam Agriculture University, Jorhat.

Sharma R C, Mahajan B V C, Dhillon B S and Azad C S. 2000. Studies on the fertilizer requirement of mango cv. Dashehari on sub-montaneous region of Punjab. *Indian Jouranl of Agricultural Research* **34**: 309–10.

Sharma J R, Kaushik R A and Panwar R D. 2008. Influence of nitrogen, phosphorus and potassium on yield and physico-chemical properties of phalsa. *Indian Journal of Horticulture* **65**: 326–7.

Sheng X F, He L Y and Huang W Y. 2003. Conditions of releasing potassium by a silicate dissolving bacteria strain NBT. *Agricultural Science* **1**: 662–6.

Shirgure P S and Srivastava A K. 2014a. Fertigation in perennial fruit crops: Major concerns. *Agrotechnology* **3**: 1.

Shirgure P S and Srivastava A K. 2014b. Effect of automated micro-irriation scheduling on productivity and quality of Nagpur mandarin. *Indian Journal of Horticulture* **71**(1): 112–6.

Shirgure P S, Srivastava A K and Huchche A D. 2014. Water requirements in growth stages and effects of deficit irrigation on productivity of drip irrigated Nagpur mandarin (*Citrus reticulata* Blanco). *Indian Journal of Agricultural Sciences* **84**(3): 317–22.

Shou W, Ram S and Vilar J M G. 2007. Synthetic cooperation in engineered yeast population. *Proceedings of National Academy of Sciences* USA. **104**: 1 877–82.

Shukla A K, Sarolia D K, Bhavana Kumari, Kaushik R A, Mahawer L N and Bairwa H L. 2009. Evaluation of substrate dynamics for integrated nutrient management under high density planting of guava cv. Sardar. *Indian Journal of Horticulture* **66**: 461–4.

Shylaja M and Rao M S. 2012. *In vitro* compatibility studies of *Trichoderma harzianum* with inorganic fertilizers. *Nematologia Mediterranea* **40**: 51–4.

Silva E D, Nogueira F D, Guimaraes P T G and Neto A E F. 2001. Coffee tree response to potassium fertilization in low and high yields. *Pesquisa Agropecuaria Bisileira* **36**: 1 331–7.

Singh S R and Banik B C. 2011. Response of integrated nutrient management on flowering, fruit setting, yield and fruit quality in mango cv. Himsagar (*Mangifera indica* L). *Asian Jouranl of Horticulture* **6**: 151–4.

Singh B, Chambey D K and Singh D K. 2002. Efficacy of biofertilizers in nutrient management in sweet orange (*Citrus sinensis* Osbeck cv. Mosambi). *Environment and Ecology* **20**: 394–6.

Singh C and Sharma B B. 1993. Leaf nutrient composition of sweet orange as affected by combined use of bio and chemical fertilizers. *South Indian Horticulture* **41**: 131–4.

Singh H P and Singh G. 2007. Nutrient and water management in guava. *Acta Horticulturae*. **735**: 389–98.

Singh J K and Varu D K. 2013. Effect of integrated nutrient management in papaya (*Carica papaya* L.) cv Madhubindu. *Asian Journal of Horticulture* **8**: 667–70.

Singh Sanjay K, Singh C P and Rashmi Panwar 2009. Response of fertigation and plastic mulch on grwoth characteristics of young Dashehri mango. *Indian Journal of Horticulture* **66**: 390–2.

Singh S R, Zargar M Y, Najar G R, Peer F A and Ishaq M I. 2011. Integrated use of organic and inorganic fertilizers with bio-inoculation yied, soil fertility and quality of apple. *Journal of Indian Society of Soil Science* **59**: 362–7.

Singh Sandeep Kumar, Thakur Nidhika and Sharma Yamani. 2012. Effective nutrient management in fruit crops. *Asian Journal of Horticulture* **7**: 606–9.

Sofo A, Celano G, Ricciuti P, Curci M, Dichio B, Xiloyannis C and Crecchio C. 2010a. Changes in composition and activity of soil microbial communities in peach and kiwifruit Mediterranean orchards under an innovative management system. *Australian Journal of Soil Research* **48**: 266–73.

Sofo A, Ciarfaglia A, Scopa A, Amele I, Curci M, Crecchio C, Xiloyanns C and Palese A M. 2010b. Soil microbial diversity and activity in a mediterranean olive orchard using sustainable agricultural practices. *Soil Use and Management* **60**: 160–7 doi:10.1111/sum.12097.

Sofo A, Palese A M, Casacchia T, Celano G, Ricciuti P, Curci M, Crecchio C and Xiloyannis C. 2010c. Genetic functional and metabolic responses of soil mircobiota in sustainable olive orchard. *Soil Science* **175**: 81–8.

Sohlegel T K, Schonherr J and Schreiber L. 2006. Rates of foliar penetration of chelated Fe (II) : Role of light, stomata, species and leaf age. *Journal of Agricultural Food Chemistry* **2**: 141–6.

Srivastava A K. 2009. Integrated nutrient management : Concept and application n in citrus. (*In*) *Citrus II. Tree, Forestry Science and Biotechnology* **3** (Special Issue 1): 32–58.

Srivastava A K. 2012. Integrated nutrient management in citrus. (*In*) *Advances in Citrus Nutrition,* pp 369–90. Srivastava A K (Ed). Springler Verlag, Netherlands.

Srivastava A K. 2013a. Nutrient diagnostics in citrus : Are they applicable to current season crop. *Agrotechnology* **2**:

Srivastava A K. 2013b. Early warning system for plant nutrient deficiency: Future Toolbox. *Agrotechnology* **2**: 3.

Srivastava A K, Das S N, Malhotra S K and Kaushik Majumdar 2014b. SSNM-based rationale of fertilizer use in perennial crops : A review. *Indian Journal of Agricultural Science* **84**: 3–17.

Srivastava A K, Huchche A D and Kumar Dinesh. 2014a. Development of INM module for sustained productivity of Citrus. (*In*) *Annual Report,* pp 40–6. National Research Centre for Citrus, Nagpur, Maharashtra.

Srivastava A K and Malhotra S K. 2014. Nutrient management in fruit crops : Issues and strategies. *Indian Journal of Fertilizer* **10**(12): 72–88.

Srivastava A K and Ngullie Ethel. 2009. Integrated nutrient management : Theory and practice. *Dynamic Soil, Dynamic Plant* **3**: 1–30.

Srivastava A K and Prakash Patil. 2014. Soil fertility indexing for acid lime growing smectite soil. *Annals of Plant & Soil Research* **16**(1): 25–8

Srivastava A K, Shirgure P S and Singh Shyam. 2003. Differential fertigation response of Nagpur mandarin (*Citrus reticulata* Blanco) on an alkaline Inceptisol under sub-humid tropical climate. *Tropical Agriculture* **80**: 91–6.

Srivastava A K and Singh Shyam. 2004. Soil and plant nutritional constraints contributing to citrus decline in Marathawada region, India. *Communications in Soil Science and Plant Analysis* **35**(17/18): 2 537–50.

Srivastava A K and Singh Shyam. 2008a. DRIS norms and their field validation in Nagpur mandarin (*Citrus reticulata* Blanco). *Journal of Plant Nutrition* **31**: 1 091–107.

Srivastava A K and Singh Shyam. 2008b. Zinc nutrition in Nagpur mandarin on Haplustert. *Journal of Plant Nutrition* **32**: 1–17.

Srivastava A K and Singh Shyam. 2008c. Citrus nutrition research in India : Current status and future strategies. *Indian Journal of Agricultural Sciences* **78**: 3–16.

Srivastava A K, Singh Shyam and Albrigo L G. 2008. Diagnosis and remediation of nutrient constraints in citrus. *Horticultural Reviews* **34**: 277–63.

Srivastava A K, Singh Shyam and Huchche A D. 2015. Evaluation of INM in citrus on Vertic Ustochrept: biometric response and soil health. *Journal of Plant Nutrition* **38**(5): 1–15.

Srivastava A K, Singh Shyam and Marathe R A. 2002. Organic citrus : Soil fertility and plant nutrition. *Journal of Sustainable Agriculture* **19**: 5–29.

Styriakova I, Styriak I, Galko D, Hradil D and Bezdicka P. 2003. The release of iron-bearing minerals and dissolution of feldspar by heterotrophic bacteria of *Bacillus* species. *Ceramics Silicáty* **47**: 20–6.

Sugiura T, Kuroda H and Sugiura H. 2007. Influence of the current state of global warming on fruit tree growth in Japan. *Horticultural Research* Japan. **6**: 257–63.

Suresh C P and Hasan M A. 2001. Studies on the response of Dwarf Cavendish banana Musa AAA to biofertilizer inoculation. *Horticulture Journal* **14**: 35–41.

Swietlik D and Zhang L. 1994. Critical Zn^{2+} activities for sour orange determined with chelator buffered nutrient solution. *Journal of Amerian Society of Horticulture Science* **119**: 693–701.

Tchabi A, Coyne D, Hountondji F, Lawvuin L, Wiemken A and Oehl T. 2008. Arbuscular mycorrhizal fungal communities in sub-Saharan savannas of Benin, West Africa, as affected by agricultural land use intensity and ecological zone. *Mycorrhiza* **18**: 181–95.

Tagaliavini M, Tonon G, Scandellari F, Quinones A, Palmieri S, Menarbin G, Gioacchini P and Masia A. 2007. Nutrient recycling during the decomposition of apple leaves (*Malus domestica*) and mowed grasses in an orchard. *Agriculture, Ecosystems and Environment* **118**: 191–200.

Tagaliavini M, Tonon G, Solimando D, Gioacchini P, Toselli M, Boldreghini P and Ciavatta, C. 2004. Nitrogen uptake by ryegrass (*Lolium perenne*) as affected by the decomposition of apple leaves ad pruning wood in soil. (*In*) *Proceedings of the 12th N Workshop: Controlling N Flows and Losses,* pp 239–41. Hatch D J (Ed.). Wageningen Academic Publishers, Wageningen, The Netherlands.

Tahía Benítez, Ana M. Rincon, M Carmen Limon and Antonio C Codon 2004. Biocontrol mechanisms of *Trichoderma* strains. *International Microbiology Journal* **7**: 249–60.

Tailor Aparna J and Joshi Bhavesh H. 2014. Harnessing plant growth promoting rhizobacteria beyond nature : A review. *Journal of Plant Nutrition* **37**: 1 534–71.

Tang Z, Zhang, Q and Hou S. 1984. The effects of mycorrhizal fungus on phosphate uptake by citrus in red earth. *Acta Mycologia Sinica* **3**: 170–7.

Tilak K V B R, Ranganayaki N, Pal K K, De R, Saxena A K, Nautiyal SC, Mittal S, Tripathi A K and Johri B N. 2005. Diversity of plant growth and soil health supporting bacteria. *Current Science* **89**: 136–45.

Tinker P B. 1982. Mycorrhiza: The present position. *Transactions of American International Congress on Soil Science*, 12th Ed. **5**: 150–66.

Tiwari D K, Hasan M A and Chattopadhyay P K. 1999. Leaf nutrient and chlorophyll content in banana (Musa AAA) under influence of *Azotobacter* and *Azospirillum* inoculation. *Environment and Ecology* **17**: 346–50.

Tiwari S C and Sharma G D. 1998. Altitudinal variation in dehydrogenase and urease activity and microbial population in soils of eastern Himalayan highlands. *Journal of Hill Reserach* **11**: 22–5.

Thuler D S, Floh E I S, Handro W and Barbosa H R. 2003. Plant growth regulators and amino acids released by *Azospirillum sp.* in chemically defined media. *Letters Applied Microbiology* **37**: 174–8.

Treeby M T. 1992. The role of mycorrhizal fungi and non mycorrhizal micro-organisms in iron nutrition of citrus. *Soil*

Biology and Biochemistry **24**: 857–64.

Umer Iqbal, Wali Vinod Kumar, Kher Ravi and Mahital Jamwal 2009. Effect of FYM, Urea and *Azotobacter* on growth, yield and quality of strawberry cv. Chandler. *Notulae Botanicae Horti Agrobotanici Cluj* **37**: 139–43.

Upadhyay G P and Kaushal R. 2008. Effect of FYM and biofertilizers in integration with inorganic fertilizers on soil fertility, yield and quality of pea. *Annals of Plant Soil Research* **10**: 130–2.

Van Veen J A, Marckx R and Van de Gejn S C. 1989. Plant and soil related controls of flow of carbon from roots through the soil microbial biomass. *Plant and Soil* **115**: 179–88.

Wang Shuang, Srivastava A K, Qiang-Sheng Wu and Fokom R. 2014. The effect of mycorrhizal inoculation on the rhizosphere properties of trifoliate orange (*Poncirus trifoliata* L. Raf.). *Scientia Horticulturae* **170**: 137–42.

Wange S S and Ranawade D B. 1998. Effect of microbial inoculants on fresh root development on grape var. *Kishmis chorni*. *Recent Horticulture* **4**: 27–31.

Welch R M, Norvell W A, Schaefer S C, Shaff J E and Kochian L V. 1993. Induction of iron (III) and copper (II) reduction in pea (*Pisum Sativum* L.) roots by Fe and Cu status: does the root-cell plasmalemma Fe(III)-chelate reductase perform a general role in regulating cation uptake? *Planta* **190**: 555–61.

Weller D M. 2007. Pseudomonas biocontrol agents of soilborne pathogens: Looking back over 30 years. *Phytopathology* **97**: 250–6.

Whipps J M. 2001. Microbial interactions and biocontrol in the rhizosphere. *Journal of Experimental Botany* **52**(Special Issue): 487–11.

Wintermute E H and Silver P A. 2010. Dynamics in the mixed microbial concourse. *Genes and Development* **24**: 2 603–14.

World Health Organisation 2014. Promoting fruit and vegetable consumption around the world. *Global Strategy on Diet, Physical Activity and Health,* pp 14–8.

Worley, R.E. 1994. Long term performance of pecan trees when potassium application is based on prescribed threshold concentration in leaf tissue. *Journal of American Society of Horticulture Science* **119**: 434–34.

Wu Qiang-Sheng and Srivastava A K. 2012. Rhizosphere microbial communities: Isolation, characterization and value addition for substrate development. (*In*) *Advances in Citrus Nutrition,* pp 169–94. Srivastava A K (Ed). Springler Verlag, Netherlands.

Wu Qiang-Sheng, Srivastava A K, Ming-Qin Cao and Jing Wang. 2014. Mycorrhizal function on soil aggregate stability in root zone and root-free hyphae zone of trifoliate orange. *Archives of Agronomy and Soil Science* http://dx.doi.org/10.1080/03650340.2014.952226

Wu Qiang-Sheng, Srivastava A K and Ying-Ning Zou. 2013. AMF-induced tolerance to drought stress in citrus. A review. *Scientia Horticultarae* **164**: 77–87.

Wu, Ting, Wang Yi, Yu Changjilang, Rawee Chiarawipa, Zhang Xinzhoing, Han Zhenhai and Lianhai Wu. 2012. Carbon sequestration by fruit trees – Chinese apple orchards as an example. Plos One 7, e38883

Xuan, Yu, Xu Liu, Tian Hui Zhu, Guang, Hai, Liu and Cui, Mao. 2011. Isolation and characterization of phosphate solubilising bacteria from walnut and their effect on growth and phosphorous mobilization. *Biology and Fertility of Soils* **47**: 437–46.

Xue Q H, Sheng J W, and Tang L. 2000. Effect of K bacteria on nutrients activation in Lou soil. *Acta Agriculturae Boreali-Occidentalis Sinica* **9**: 67–71.

Yadav K, Prasad V, Mandal K and Ahmed N. 1992. Effect of coinocuation (*Azospirillum* and *Rhizobium* strains) on nodulation, yield, nutrient uptake and quality of lentil [*Lens culinaris*]. *Lens Newsletter* **19**: 29–31.

Yadav Rajesh, Singh Baksh Hari, Singh H K, Yadav A L. 2007. Effect of integrated nutrient management on productivity and quality of aonla (*Emblica officinalis* Gaetm.) fruits. *Plant Archives* (1&2): 881–3.

Yang Y, Wang H, Tang J, and Chen X. 2007. Effects of weed management practices on orchard soil biological and fertility properties in southeastern China. *Soil Tillage Research* **93**: 179–85.

Yao H, He Z, Wilson, M J and Campbell, C D. 2000. Microbial biomass and community structure in a sequence of soils with increasing fertility and changing land use. *Microbial Ecology* **40**: 223–37.

Yedidia I, Srivastava A K, Kapulnik Y and Chet I. 2001. Effects of *Trichoderma harzianum* on microelement concentration and increased growth of cucumber plants. *Plant and Soil* **235**: 235–42.

Yong-Ming Huang, Srivastava A K, Ying-NingZou, Qiu-DanNi, YuHan and Qiang-ShengWu. 2014. Mycorrhizal - induced calmodulin mediated changes in antioxidant enzymes and growth response of drought-stressed trifoliate orange. *Frontiers in Microbiology* **5**: 682–8. doi:10.3389/fmicb.2014.00682

Young C C, Hupfer H, Siering C, Ho M J, Arun A B, Lai W A, Rekha P D, Shen F Y, Hung M H, Chen W M, and Yassin A F. 2008. *Azospirillum rugosum* sp., isolated from oil contaminated soil. *International Journal of Systematic Evolutionary Microbiology* **58**: 958–63.

Zahir A, Zahir, Mohmmad, Arshad, William T, and Frankenberger Jr. 2003. Plant growth promoting rhizobacteria : Applications and perspectives in agriculture. *Advances in Agronomy* **31**: 97–166.

Zaman, Q U, and Schumann A W. 2006. Nutrient management zones for citrus based on variation in soil properties and tree performance. *Precision Agriculture* **7**: 45–63.

Zeng, Q, Brown P H, and Holtz B A. 2001. Potassium fertilization affects soil K, leaf concentration, and nut yield and quality of mature pistachio trees. *HortScience* **36**: 85–9.

Zhang Ze-Zhi, Srivastava A K, Qiang-Sheng Wu and Guo-Huai Li. 2015. Growth performance and rhizospheric traits of peach (*Prunus persica*) in response to mycorrhization on replant versus non-replant soil. *Indian Journal of Agricultural Sciences* **85**(1): 125–30.

Zhang Q and Wang G H. 2005. Studies on nutrient uptake of rice and characteristics of soil microorganisms in a long-term fertilization experiments for irrigated rice. *Journal of Zhejiang University of Science* **6**: 147–54.

Zou H, Huan S, Ding G, Yan Z, Yue Ye, Wen M, Chen H C, Bin L, Jing B, and Ding H. 1994. Effect of soil microbes on growth and production of citrus fruits. *Journal of Fruit Science* **11**: 19–22.

Zou Y N, Srivastava A K, Wu Q S and Huang Y M. 2014a. Increased tolerance of trifoliate orange (*Poncirus trifoliata*) seedlings to waterlogging after inoculation with arbuscular mycorrhizal fungi. *Journal of Animal & Plant Science* **24**(5): 1 415–20.