The soil microorganisms being responsible for production, protection, and maintenance of soil health and fertility have been known for centuries. However, in the present day intense agricultural practices the contributions of these microorganisms have been overlooked, since their effects are more pronounced under sustainable conditions as compared to nutrient insufficient soil environment. Use of excessive inorganic fertilizers and pesticides in intensively cropped soil has destroyed the microbial equilibrium, microorganisms harmful to plant growth have predominated over the beneficial ones. However, the efforts to understand the phisiology, biochemistry, and genetics of these organisms which indirectly benefit the plants in nutrient absorption, protection, and maintenance of soil fertility. The Book "Biotechnology in Soil Microorganisms for Sustainable Crop Production" is a compilation of such beneficial soil microorganisms which have been recognized as plant nutrient solubilizers or mobilizers, plant growth promoters, plant health protectors, pathogen suppressors, antagonists, and pollutant detoxifiers and organic matter degraders.

The biochemical and physiological aspects of plant nutrient supply have been extensively discussed by molecular approaches taking advantage of the microorganism or the plant system to get maximum benefits from a plant-microbe association or interaction. Some studies carried out with soil microorganisms involved in plant growth promotion, disease suppression, pest control, and pollutant degradation have been discussed with biotechnological approaches to tailor these organisms to enhance the effectiveness of the process in which they are involved. The scale production of the organism and the end point of metabolism involved in benefiting the plant, with its properties, are also elaborated.
Role of Free Living and Associative Diazotrophs in Non-legumes

S.P. Wani
Soil Science and Agroclimatology Division,
ICRISAT-Asia Centre,
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1. Introduction
2. Crop responses to inoculation
3. Nutrient uptake
4. Effect of soil nutrients
5. Organic matters and inoculations
6. Interaction between nitrogen fixing bacteria and other microorganisms
7. Mechanisms of response
8. Recent advances in non-legume nitrogen fixation
9. Future needs
10. Conclusions
11. References

1. INTRODUCTION

The quantum jumps in cereal crop yields during the era of "green revolution" in agriculture in the 1960's were largely through the adoption of highly N-fertilizer responsive plant genotypes. Inspite of an unlimited supply of N₂ in the air, manufacturing of 1 kg of fertilizer N requires 18.5 MCal, six times more energy than that needed to produce either P or K fertilizer (1). Manufacturing the
fertilizer for today's needs requires \(544 \times 10^9\) M\(\text{J}\) of fossil fuel energy (2, 3), which is equivalent to about 13 million tonnes of oil - a non-renewable resource. In India, we have to reach the estimated target of 230-240 million tonnes of foodgrains by 2000 AD. On the other hand, the demand for fertilizer nitrogen produced by using non-renewable fossil fuels cannot be met through domestic production. In such a scenario, help of microbes which do not need fossil energy is of immense value for increasing soil productivity in India where most of the agriculture is low-input farming.

A survey of 200 fields in the traditional sorghum and millet-growing areas in North-Western India showed the most probable number (MPN) of \(\text{N}_2\) fixers varying from \(10^2 - 10^3\) g\(\text{t}\) soil. Out of 3760 isolates obtained from these soils following MPN and dilution plate count technique, 42% isolates showed \(\text{N}_2\)ase activity in vitro (6). In another study, out of 546 different isolates obtained from the rhizosphere of pearl millet grown at ICRISAT Center, only 17% isolates showed \(\text{N}_2\)ase activity in vitro. Pearl millet rhizosphere was dominated by azospirilla, constituting 72% of total \(\text{N}_2\)-fixing isolates followed by enterobacters (12%), azotobacters (11%) and pseudeudomonads (5%) (15).

It is commonly thought that these bacteria could be exploited to increase crop yields through increased BNF. To increase crop yields, the route of artificial inoculation of plants with \(\text{N}_2\)-fixing bacteria has been tried. Many experiments have been performed in several countries to investigate the effects of inoculation of various strains of \textit{Azotobacter chroococcum} and \textit{Azospirillum} spp. on cereals and grasses. Several field experiments in Belgium, Brazil, Czechoslovakia, Egypt, Israel, India, Germany, Poland, USA and erstwhile USSR with different crops, inoculated with different \(\text{N}_2\)-fixing bacteria, showed increased yields and / or increased N accumulation by plants, and sometimes resulted in decreased yields because of inoculation.

In this article, the results of several field inoculation trials with azospirilla and azotobacters, mechanisms of increasing crop yields and the extent of BNF's contribution to sustainable agriculture are reviewed. Recent developments in the area of non-legume \(\text{N}_2\)-fixation are also discussed.

**2. CROP RESPONSES TO INOCULATION**

Plant responses to inoculation with azotobacters and azospirilla in cereals and non-cereals are often reported in terms of increased grain yield, plant biomass yield, nutrient uptake, grain and tissue N contents, nitrogenase activity, early flowering, tiller numbers, greater plant height, leaf size, increased enzyme levels in plant parts, increased number of spikes and grains per spike, thousand grain weight, increased root length and incidences of reduced insect and disease infestation (8, 16). Recent reviews (9, 17) have evaluated the worldwide crop responses to inoculation with azotobacters and azospirilla. The results indicated that in many cases inoculations increased plant yields but such increases were variable (statistically...
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Wani (8) reviewed the comprehensive data obtained from field experiments conducted in erstwhile USSR which showed that out of 1095 experiments, 890 (81%) experiments showed increases in yields of cereals and vegetables and the increases amounted to 10% in only 514 (47%) experiments. Similarly, several subsequent field experiments showed increased crop yields due to Azotobacter inoculation (Table 1). In the Estonian S.S.R., region, results of 117 field experiments on the use of Azotobacter demonstrated that Azotobacter is effective only in soil with a native Azotobacter population. This observation looks strange since it is generally thought that inoculation is successful in soils that have very low or no population of the inoculant bacteria. Further, it was suggested that instead of Azotobacter inoculation it would be more convenient to enhance the growth of the native Azotobacter population in the soil by treating seeds with trace elements and other growth factors (18). In Australia, out of 71 field trials with Azotobacter inoculation of wheat, in 28 trials grain yields increased by 5%, in 4 trials negative results were observed and in 39 trials no effect on grain yields were observed (19).

Table 1. Summary of cereal responses to Azotobacter inoculation in different regions of the USSR (8).

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<tr>
<th>Crop</th>
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<th>Av. % increase in yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring wheat</td>
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</tr>
<tr>
<td>Winter wheat</td>
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<td>12.7</td>
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<td>8.6</td>
</tr>
<tr>
<td>Foxtail millet</td>
<td>2</td>
<td>39.1</td>
</tr>
<tr>
<td>Oats</td>
<td>73</td>
<td>12.3</td>
</tr>
<tr>
<td>Rye</td>
<td>7</td>
<td>19.1</td>
</tr>
<tr>
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<tr>
<td>Corn</td>
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In Israel, field inoculation experiments with Azospirillum were carried out using different cereal crops, varieties, and different fertilization levels (23). These experiments were conducted on large plots (200 - 1000 m²) with 4 - 6 replications and the agronomic practices used were identical to those used for commercial production. Thirty-one such field experiments were conducted and in most cases, the effect of Azospirillum varied with the seasons, years, and the crop (Table 3). In general, inoculation of the C-4 plants corn, sorghum, Punicum, and Setaria showed greater yield increases than the inoculated spring wheat, a C-3 plant. With the summer crops, 75% of the experiments showed significant increases and 90% of the experiments showed increases >5%. The optimum temperature for Azospirillum growth is 32 - 35°C and it is possible that bacterial activity, including BNF was greater in the summer, particularly in irrigated crops. During vegetative phase of wheat growth, the soil temperatures in Israel are 10 - 15°C; nevertheless, inoculation of wheat with Azospirillum also showed significant increases in foliage and grain yield with lower increases than the summer crops.
increased N assimilation by plants (26-29). In pearl millet inoculation with *Azospirillum* or *Azotobacter* generally increased total plant N assimilation, and such increases were higher at sub-optimal levels of applied N with inoculation (8). Based on several field trial analysis, the average increase in N assimilation by inoculated pearl millet was found to be about 5 kg ha\(^{-1}\) (8). Pearl millet inoculation experiments were conducted for three consecutive years in the same plot. Following three years of inoculation with N\(_2\)-fixing bacteria, N uptake by a pearl millet cv. ICMV1 was studied at 0, 20 and 100 kg N application under field conditions. In case of 20 kg N ha\(^{-1}\) treatment, apparent fertilizer recovery by plants in uninoculated treatment was 45% whereas the apparent fertilizer recovery in case of *Azosp. lipoferum* inoculated treatment was 86% and with *Azlb. chroococcum* it was 113%. In case of 100 kg N ha\(^{-1}\) treatment inoculation with N\(_2\)-fixing bacteria increased apparent fertilizer N recovery marginally by 7% over the uninoculated treatment (55 vs. 48%). Similarly, maximum increased N assimilation (21 kg N ha\(^{-1}\)) due to inoculation with *Azosp. brasilense* was observed in 20 kg N ha\(^{-1}\) treatment over the 20 kg N ha\(^{-1}\) alone showing 105% apparent plant N recovery of applied N (22).

### Table 4. Mean grain, total plant biomass yield and total plant N uptake by pearl millet inoculated with N\(_2\)-fixing bacteria with different N levels (20).

<table>
<thead>
<tr>
<th>Levels of N (kg ha(^{-1}))</th>
<th>Bacterial culture</th>
<th>uninoculated control</th>
<th>Mean</th>
<th>SE ±</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean grain yield (t ha(^{-1}))</td>
<td><em>A. lipoferum</em></td>
<td><em>A. chroococcum</em></td>
<td>Mean</td>
<td>SE ±</td>
</tr>
<tr>
<td>1.8(16)</td>
<td>1.8(16)</td>
<td>1.5</td>
<td>1.7</td>
<td>0.059 NS</td>
</tr>
<tr>
<td>2.0(10)</td>
<td>1.9(4)</td>
<td>1.8</td>
<td>1.9</td>
<td>0.033*</td>
</tr>
<tr>
<td>2.0(6)</td>
<td>2.0(3)</td>
<td>1.9</td>
<td>2.0</td>
<td>0.059 NS</td>
</tr>
<tr>
<td>Mean</td>
<td>1.93</td>
<td>1.88</td>
<td>1.76</td>
<td>0.033*</td>
</tr>
</tbody>
</table>

Total plant N uptake (kg ha\(^{-1}\)), mean of 2 locations

<table>
<thead>
<tr>
<th>Levels of N (kg ha(^{-1}))</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>32.2(27)</td>
</tr>
<tr>
<td>20</td>
<td>37.0(13)</td>
</tr>
<tr>
<td>40</td>
<td>39.2(8)</td>
</tr>
<tr>
<td>Mean</td>
<td>36.1</td>
</tr>
</tbody>
</table>

P = 0.01, NS = Nonsignificant.
Figures in parentheses indicate % increase over controls.

### 5. ORGANIC MANURES AND INOCULATIONS

Nitrogen-fixing bacteria associated with non-legumes require carbon for their growth and activity in soil. Addition of organic substances introduced into the low organic matter containing tropical soils serve as carbon source for N\(_2\)-fixing bacteria and also help the bacteria to overcome the antagonistic effect of soil microflora. Increased nitrogenase activity was observed in the soil when straw was incorporated and the activity enhanced further under warm and moist conditions (31). Similarly, addition of 3% w/w farmyard manure to sand considerably enhanced nitrogenase activity associated with sorghum and millet roots (32). Incorporation of straw (5% w/w) into Nile Delta Soil together with *Azospirillum* inoculation increased dry matter, nitrogen content, and plant height of 12-week old maize plants. Nitrogenase activity associated with corn roots was also increased (33). The inoculation experiment
The soil microorganisms be production and protection and maintenance of soil health and fertility are known for centuries. However, in the present day intense agricultural practices the contributions of these microorganisms have been overlooked, since their effects are more pronounced under sustainable conditions as compared to nutrient insufficient soil environment. Use of excessive inorganic fertilizers and chemical pesticides in intensively monocropping has destroyed the microbial equilibrium. Microorganisms harmful to plants predominated over the beneficial. The Soil Biologists continued to highlight the role of the beneficial microorganisms in the health of the soil, in understanding the phisiology and the genetics of these organisms which indirectly benefit the plants in nutrient production and protection and maintenance of soil fertility. The Book "Biotechnology in Sustainable Crop Production" is a compilation of many beneficial soil microorganisms which have been recognized as plant nutrient solubilizers or mobilizers, plant health promoters, antagonists, suppressors, pathogen, rhizosphere colonizers, pesticide degraders, decomposers and organic matter decomposers.

The biochemical and physiological aspects of plant nutrient supply through microorganisms (mainly nitrogen and phosphorus) have been discussed. Molecular approaches attempt to modify the microorganisms, or to get maximum benefits from the plant system to the plant-microbe association or interaction. Similarly, molecular biological studies carried out with soil involved in plant growth suppression, pest control, disease and pollutant detoxification have been discussed with biotechnological approaches to tailoring these organisms to enhance the effectiveness of the process in which they are involved. The production technologies for large scale production of the organisms or the end products involved in benefiting the plant, with limitations involved in the processes, are also elaborated.
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1. INTRODUCTION

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Diazotrophs like *Herbaspirillum* spp. grow endophytically in the stems and leaves of sugarcane. There is evidence to show that *Acetobacter diazotrophicus* is the main contributor of endophytic BNF, which according to N-balance studies was found to be as high as 150 kg N ha$^{-1}$ y$^{-1}$ in sugarcane (9). Another N$_2$-fixing endophyte which is of considerable interest is *Azotococcus*. This diazotroph inhabits the roots of Kollar grass (Leptochloa fissa) which yields 20-40 t of hay ha$^{-1}$ y$^{-1}$ without the addition of any N fertilizer in saline-sodic, alkaline soils having low fertility (10). Recent studies have demonstrated the endophytic colonization of rice roots by other N$_2$-fixing bacteria *Alcaligenes faecalis* (11, 12) and *Herbaspirillum* spp. (13). *Herbaspirillum* spp. have also been isolated from stems and leaves of rice (13). Hureck et al. (14) showed that the N$_2$-fixing endophyte *Azotococcus* BH72 has the ability to invade and colonize rice roots.

Although many genera and species of N$_2$-fixing bacteria are isolated from the rhizosphere of various cereals, mainly members of *Azotobacter* and *Azospirillum* genera have been widely tested to increase yields of cereals under field conditions. These bacteria are stimulated in the rhizosphere of cereal crops and a selection for particular type of bacteria also occur in the root zone. *Azospirilla* and *azotobacters* are active N$_2$ fixers under laboratory conditions, generally found wherever these are sought and can use a variety of carbon and energy sources for their growth on combined N or N$_2$ (8).

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It is commonly thought that these bacteria could be exploited to increase crop yields through increased BNF. To increase crop yields, the route of artificial inoculation of plants with N$_2$-fixing bacteria has been tried. Many experiments have been performed in several countries to investigate the effects of inoculation of various strains of *Azotobacter chroococcum* and *Azospirillum* spp. on cereals and grasses. Several field experiments in Belgium, Brazil, Czechoslovakia, Egypt, Israel, India, Germany, Poland, USA and erstwhile USSR with different crops, inoculated with different N$_2$-fixing bacteria, showed increased yields and / or increased N accumulation by plants, and sometimes resulted in decreased yields because of inoculation.

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### 4. EFFECT OF SOIL NUTRIENTS

Soil and fertilizer N affect the response to inoculation. Largest differences in yields are obtained when the soil is adequately but not excessively fertilized. In a multi-location experiments with pearl millet, higher increases in grain, plant biomass, and total N uptake were observed with zero N + inoculation and the extent of response declined with the increasing levels of applied N (Table 4). In another set of experiments conducted at four locations in India with pearl millet over five years it was observed that the maximum benefits of inoculation was seen either at 0 or 10 kg N ha\(^{-1}\) application than with 20 or 40 kg N ha\(^{-1}\) application (30). Grain yields obtained from zero N treatments inoculated with N\(_2\)-fixing bacteria were similar to the yields from the non-inoculated plots receiving 20 kg N ha\(^{-1}\). It is therefore not uncommon to observe yield increases equivalent to 20 kg N ha\(^{-1}\) depending on locations, soil fertility and other factors (8).

### Table 4. Mean grain, total plant biomass yield and total plant N uptake by pearl millet inoculated with N\(_2\)-fixing bacteria with different N levels (20).

<table>
<thead>
<tr>
<th>N levels (kg ha(^{-1}))</th>
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<th>uninoculated</th>
<th>Mean</th>
<th>SE +</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>A. lipoferum</em></td>
<td><em>A. chroococcum</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain yield (t ha(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>1.8(16)</td>
<td>2.0(10)</td>
<td>1.5</td>
<td>32.2(27)</td>
</tr>
<tr>
<td>NS</td>
<td>0.003*</td>
<td>0.01</td>
<td></td>
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<tr>
<td>V</td>
<td>20</td>
<td></td>
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<tr>
<td>Total plant N uptake (kg ha(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>32.2(27)</td>
<td>29.9(18)</td>
<td>25.3</td>
<td>29.1</td>
</tr>
<tr>
<td>20</td>
<td>37.0(13)</td>
<td>36.6(12)</td>
<td>32.6</td>
<td>35.4</td>
</tr>
<tr>
<td>40</td>
<td>39.2(8)</td>
<td>37.3(3)</td>
<td>36.2</td>
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<tr>
<td>Mean</td>
<td>36.1</td>
<td>34.6</td>
<td>31.4</td>
<td></td>
</tr>
</tbody>
</table>

\(P = 0.01\), NS = Nonsignificant.

Figures in parentheses indicate % increase over controls.

### 5. ORGANIC MANURES AND INOCULATIONS

Nitrogen-fixing bacteria associated with non-legumes require carbon for their growth and activity in soil. Addition of organic substances introduced into the low organic matter containing tropical soils serve as carbon source for N\(_2\)-fixing bacteria and also help the bacteria to overcome the antagonistic effect of soil microflora. Increased nitrogenase activity was observed in the soil when straw was incorporated and the activity enhanced further under warm and moist conditions (31). Similarly, addition of 3% w/w farmyard manure to sand considerably enhanced nitrogenase activity associated with sorghum and millet roots (32). Incorporation of straw (5% w/w) into Nile Delta Soil together with *Azospirillum* inoculation increased dry matter, nitrogen content, and plant height of 12-week old maize plants. Nitrogenase activity associated with corn roots was also increased (33). The inoculation experiment
conducted for 2 years in the same plot with pearl millet showed that addition of FYM at 5 t ha\(^{-1}\) increased the yield over no FYM plot and further inoculation with \(A.\) lipofenum or \(A.\) chroococcum along with FYM increased the yields by 9% and 12% over the FYM alone treatment (26). In field studies, inoculation of rice with Azotobacter along with green manuring with Sesbania, Glycinebina, or Sunnhemp, and addition of paddy straw, increased grain yield by 9 - 19% and straw yield by 7-21% over uninoculated controls (34).

6. INTERACTION BETWEEN \(N_2\)-FIXING BACTERIA AND OTHER MICROORGANISMS

For simultaneous application of two or more biofertilizers to promote plant nutrition, interactions between \(N_2\)-fixing bacteria and other beneficial microorganisms like cellulose decomposers, phosphate solubilizers and mycorrhizae have been studied. Simultaneous application of \(A.\) chroococcum and \(B.\) polymyxa performed better at 80 and 100 kg N ha\(^{-1}\) (with 9% increase above uninoculated control) than at 120 and 160 kg ha\(^{-1}\) (with marginal reduction) (35). Simultaneous inoculation of barley with \(A.\) chroococcum and \(A.\) brasilense increased grain yield by 19% over uninoculated control as compared to increases of 9% by \(A.\) chroococcum and 4% by \(A.\) brasilense inoculation (36).

In a field experiment, simultaneous inoculation of sorghum with \(A.\) brasilense and Glomus fuscum (Vesicular- arbuscular mycorrhizal fungus) showed significant \((P = < 0.05)\) increase in grain and fodder yield over uninoculated control and single inoculation with either \(A.\) brasilense or \(G.\) fuscum (30). The entry of Azotobacter \(diazotrophicus\) into sugarcane/sweet sorghum roots is facilitated by VA mycorrhizia (37).

7. MECHANISMS OF RESPONSE

\(Azospirillum\), and \(Azotobacter\) species initially selected for inoculation experiments because of their \(N_2\)-fixing ability and close association with plant roots. The mechanisms by which the plants inoculated with these bacteria derive positive benefits in terms of increased grain, plant biomass and N uptake are attributed to small increase in N input from fixation, development and branching of roots, production of plant growth hormones, enhancement in uptake of \(NO_3^-, NH_4^+, PO_4^{3-}, K^+, Rb^+\) and \(Fe^{2+}\) and improved water status of the plants. In certain experiments high nitrogenase activities (1000 to 3000 nmol C\(_2\)H\(_4\) h\(^{-1}\) g\(^{-1}\) of dry roots) have been observed in case of inoculated plants (28, 33) which could account for total N gains by inoculated plants. However, as nitrogenase activities are one time measurements, such results cannot be extra polated confidently over the whole season. In several experiments even at flowering stage when nitrogenase activity is at peak; the activity recorded is low for inoculated plants which could not explain the N gains (16, 22). In trials with pearl millet inoculated with \(N_2\)-fixing bacteria, nitrogenase activity increased in field but such increased activity was observed only during later stages of plant growth for a shorter period. As most of the N required for plant growth in pearl millet and sorghum is taken up before flowering and increased nitrogenase activity was observed after flowering for a shorter period, the increased activity may not account solely for the increased N uptake observed (22). Pearl millet and sorghum grown in tubes containing either agar medium or sand: FYM or an Alfisol and inoculated with \(A.\) lipofenum and \(A.\) chroococcum showed increased root development, more lateral roots and also more root hairs (5, 16). There is still no direct evidence to support claims that hormonal process take place under field conditions. The separation of the effects on plant growth because of bacterial \(N_2\) fixation from those resulting from hormone production by the bacteria may be achieved using mutants lacking either the ability to fix \(N_2\) or to synthesize hormonal compounds. Inoculation of sorghum with \(Azotobacter\) and \(Azospirillum\) resulted in marked decline of shoot fly (\(Atherigona soccata\) Rond.) damage as compared to uninoculated control (38 - 40). Plants inoculated with \(Azospirilla\) had increased levels of phenol contents in shoots (38).

8. RECENT ADVANCES IN NON-LEGUME \(N_2\) FIXATION

Recently, several approaches using techniques in the area of molecular biology have raised the hopes that at least some non-leguminous field crops become independent of soil nitrogen (41). A meeting held at the International Rice Research Institute (IRRI) in 1992 assessed the feasibility of nodulation and \(N_2\) fixation in rice (42). Following four major short and long-term approaches to address this problem were identified by the workshop participants:
(a) Improve N supply to rice by achieving the colonization and invasion of rice roots by diazotrophic bacteria including ammonia-excreting strains.

(b) Determine the defence responses of rice to rhizobia / Frankia and find ways to circumvent them to lay the foundation for engineering the plant to nodulate in the presence of rhizobia / Frankia.

(c) Begin assembling active nitrogenase in rice by identifying or creating barriers to protect the enzyme from oxygen.

(d) Improve understanding of N metabolism in rice; assess and model the impact of N2 fixation on N, C, and energy budgets of the plant and identify control points where N availability regulates photosynthesis, carbohydrate partitioning and leaf senescence.

Under sterile conditions inoculated Alcaligenes faeialis attached themselves to the rice root surface, particularly on root hairs near the axis of lateral root with main root (12). Scanning electron microscopic studies revealed that inoculated cells invaded rice roots through epidermis and colonized intercellular spaces mainly in cortex and secondary xylem tissues. Inoculation of genetically engineered strains of Alcaligenes faeialis which constitutively express nif A both in pot and field conditions increased rice yield by 5 to 8% and fixed 13 - 20% more N2 compared to the N2 fixed by wild-type strain. Sprent and de Faira (43) while studying Parasponia-Rhizobium, a non-legume symbiosis emphasised that many accepted dogmas for 'normal' symbioses, for example root hair infection and the release of bacteria from infection threads before they differentiate into N2-fixing forms are not universal. This suggests that a range of systems need to be studied for exploiting the BNF. Aloysius and Paton (44) explored the concept of artificially establishing symbioses between plants and L-forms of bacteria. L-forms of Azotobacter, Pseudomonas syringae, Bacillus polymyxa and Beijerinckia indica were all considered as capable of penetration to plant tissue. Although, no tests for nitrogenase activity were performed, such approaches offer possible means of allowing non-legumes such as cereals to fix their own N.

Formation of nodular structures on nonleguminous field crops by rhizobia promoted by enzymatic cell wall degradation coupled with polythylene glycol has been reported (46, 47). This apparently assists the entry of rhizobia, though, nitrogenase activity in the resulting nodules was barely detectable. Bradyrhizobium parasporum is capable of infecting the roots of oilseed rape without enzyme treatment (46). Nie and his colleagues at Shandong University in China have studied the nodule inducing effect of 2, 4-dichlorophenoxy acetate (2,4-D) on the roots of large number of plant species, including wheat (47). This approach resulted from an initial observation by Nie while using plant tissue culture medium containing, 2,4-D. These nodules formed irrespective of whether the roots were inoculated with rhizobia or not. Kennedy et al. (48) termed such nodules formed by 2,4-D treatment as para-nodules (para = beyond) to emphasize their distinctness from legume nodules. Rhizobia were found to have the ability to attach themselves to rice roots (49). Nodulation of rice has also been achieved at low frequencies by applying rhizobia either to normal roots (50) or to enzyme-treated roots in the presence of polythene glycol and calcium chloride (46). Using 2,4-D treatment of wheat and Azospirillum as microsymbiont, encouraging results have been obtained in this new model of a N2-fixing symbiosis in non-legumes (51). Substantial rates of ethylene production by the plant seedling treated with 2,4-D however has been reported in absence of both C2H2 and azospirilla. Under sterilized conditions ammonia excreting A. brasilense colonized 2,4-D induced para- nodules in maize roots, and the nitrogenase activity inside the para-nodules was less sensitive to oxygen than in non- para-nodulating roots (52). If this in-vitro model can be shown to be a working systems in the field, application of para- nodulation in agricultural crops require further studies. It is not known whether the introduced diazotrophs can selectively colonize para-nodules (52). However, we need to answer several questions for example: (i) Is there a direct transfer of fixed nitrogen to the host plant, or is fixation simply bound to the growth of Azospirillum? (ii) What will be the carbon costs to plants for sustaining para-nodules? (iii) how long the para- nodules will remain as active sites of nitrogen fixation? (iv) Is the oxygen requirement of N2 fixation likely to be satisfied in para-nodules? etc. Further, the agricultural use of 2,4-D is discouraged because of toxicity and slow degradability. In a recent paper Ladha and Reddy (52) have elaborately discussed the necessity and possibilities for extension of nitrogen fixation to rice and opined that presently there are many potential obstacles to the development of BNF capability in rice through nodulation or nif gene transfer. At the moment, urgent need is to identify stable and effective endophytic diazotroph for rice.

Plant pathogenic bacteria Agrobacterium tumefaciens (54) and Pseudomonas rubrisubalbicans (55) causing mottled stripe disease in
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9. FUTURE NEEDS

While the progress through use of methods used in biotechnology may lead to breakthroughs in due course, concerted efforts through conventional microbiological techniques will have to be put towards understanding the complex systems. Such studies will enable to identify stable and effective endophytic associations like *Acetobacter diazotrophicus* in sugarcane contributing positive N balance with other nonlegumes. Further, very little is known about the competitiveness of microorganisms and the factors governing it. Research is needed in soil physical and chemical factors that influence both the establishment in the rhizosphere and the expression of its traits fully for benefitting the crop. Once these factors are identified, it may be possible to manipulate them in the field so as to enhance the consistency of their performance. There is need to study the reasons for decline in the numbers of inoculated bacteria (8) and to find the agronomic practices that may help to establish the inoculated bacteria in large numbers in the rhizosphere. The potential for strain selection for crops does exist. However, the criteria for strain selection need to be changed looking into the results of the response mechanisms. Research to understand the mechanisms by which the introduced microorganisms benefit the crop is critically important. Identifying important traits would enable efficient selection of new strains. Efficient strains with selective traits to perform well under adverse conditions like soil salinity, moisture stress, need to be selected or developed and tested for their performance.

More research on formulation and efficient delivery of the biofertilisers is needed. Search for newer synthetic carrier materials which can be uniform, non-toxic, simple to use and support large populations of introduced microorganisms for a longer time must be pursued vigorously.

10. CONCLUSIONS

In order to reach the estimated target of 240 million tonnes of food grain, 20 million tonnes of pearl millet, 5 million tonnes of sorghum, and 60 million tonnes of biofertiliser (excluding blue green algae) is 84,800 tonnes per year for India (57). It is an important task to ensure supply of such a large quantity of biofertilizers to farmers in India as availability of “good quality” inoculants has been identified as one of the important constraints responsible for successful use of BNF technology (58). For success of biofertilizers in countries like India, concerted efforts right from production, demonstration to distribution are needed. The next step is convincing and educating the farmers regarding the benefits of these inoculants for sustaining productivity of our soils. In many cases the increases are smaller (for eg. 50 to 230 kg ha⁻¹ in different crops @ 10% an average increase) than the changes in yield due to climatic and biotic (diseases insects) variations. In cases where enough soil N is available for crop yield the yields may not increase but less soil N would be utilized for producing same yield. There is a need to demonstrate the benefits from BNF technology in terms of maintenance or improvement of soil fertility through long-term experiments. In case of biofertilizers consistent benefits in terms of appreciable increase in economic crop

microbes through BNF or improved fertilizer use efficiency. Comprehensive reviews on non-symbiotic/associative N₂-fixing bacteria have shown 60% of occurrence of success with statistically significant increases in yield up to 30% due to inoculations. On an average dryland crops such as pear millet and sorghum show 10 - 12% increase in yields and maize, wheat, and rice grown with better management and inputs show 15 - 20% increase in yields over un inoculated control due to inoculation with N₂-fixing bacteria. In India sorghum is gown over 12.9 million ha with an average production of 900 kg ha⁻¹, pear millet on 9.5 million ha with 530 kg ha⁻¹ average yield, rice on 42 million ha with 1880 kg ha⁻¹ grain yield, wheat on 24.9 million ha with 2370 kg ha⁻¹ grain yield and maize on 5.9 million ha with 670 kg ha⁻¹ average grain yield (56). Assuming that inoculation with N₂-fixing bacteria increases the yield by 10% on 50% of the area sown with sorghum, pear millet, rice, wheat and maïze in India, the increased yields would be about 0.57 million tonnes for sorghum, 0.25 million tonnes for pear millet, 3.9 million tonnes for rice, 2.9 million tonnes for wheat and 0.47 million tonnes for maize. How much of such increased yields are due to increased BNF, due to increased N uptake or increased N use efficiency by plants is an academic question. However, to cover such a large area with “good quality” bacterial inoculants is not an easy task. Estimated requirement of biofertilizers (excluding blue green algae) is 84,800 tonnes per year for India (57). It is an important task to ensure supply of such a large quantity of biofertilizers to farmers in India as availability of “good quality” inoculants has been identified as one of the important constraints responsible for successful use of BNF technology (58). For success of biofertilizers in countries like India, concerted efforts right from production, demonstration to distribution are needed. The next step is convincing and educating the farmers regarding the benefits of these inoculants for sustaining productivity of our soils. In many cases the increases are smaller (for eg. 50 to 230 kg ha⁻¹ in different crops @ 10% an average increase) than the changes in yield due to climatic and biotic (diseases insects) variations. In cases where enough soil N is available for crop yield the yields may not increase but less soil N would be utilized for producing same yield. There is a need to demonstrate the benefits from BNF technology in terms of maintenance or improvement of soil fertility through long-term experiments. In case of biofertilizers consistent benefits in terms of appreciable increase in economic crop
yields are not observed by farmers due to the factors mentioned above. In such a case government/society has to take action for maintaining the soil resource, as is the case of soil and water conservation practices. Along with the use of good quality biofertilizers, optimum management practices need to be provided to ensure maximum contribution from the BNF. In the tropics plant residues are not generally incorporated in soil. There is need to generate plant material on farm (eg. growing legumes and nonlegumes on farm bunds, growing short duration crops after harvesting of main crop etc.) for incorporation in soil. Such incorporation would enhance the nonsymbiotic N2-fixation associated with microbial degradation of the residues which would help in improving the soil fertility status and also to serve as the carbon source for rhizosphere activity of the inoculated bacteria. A holistic approach to harness the benefits from N2-fixing bacteria associated with nonlegumes is needed.

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