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AGRICULTURAL NITROGEN MANAGEMENT FOR SUSTAINABLE DEVELOPMENT AND GLOBAL FOOD SECURITY

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Abstract:

The current world population of 7.1 billion is expected to reach 9.1 billion by 2050, and world food production will need to rise by 70 % in developed and double in the developing world. Undoubtedly, the application of industrially fixed nitrogen fertilizers has revolutionized the crop productivity, but has dramatically increased the emissions of reactive nitrogen in the atmosphere, soil and water affecting adversely the environmental and human health, consequently climate change. To bring down the use of synthetic nitrogen in agriculture and at the same time increasing crop productivity is a challenge to the regional and world scientists, technologists and policy makers. There exist two viable options to achieve this goal. First is to increase the efficiency of nitrogen use in crops and the second to encourage biological nitrogen fixation, which can also improve soil fertility, and considering the ways to develop successful symbiotic (cyanobacterial/ bacterial) nitrogen fixing crops.

Keywords: biofertilizer, cyanobacteria, nitrogen fixation, nitrogen use efficiency, symbiosis, synthetic nitrogen

Introduction

No other invention has influenced the world civilization as that of the early 20th century invention Haber-Bosch process, i.e., taking nitrogen from the air (N_2) and reducing it to reactive forms of nitrogen, which earned two Nobel Prizes in chemistry, Haber in 1918 and Bosch in 1931. This made Green Revolution a success and feasible to nourish the ever-increasing global population and reversing the scenario of food crisis; while population doubled, food supply tripled. To-day half of the world population is fed by crop production grown on industrially fixed nitrogen. Since nitrogen is one of the most limiting nutrients for plants and is often required in high amount, its availability (industrially fixed N) has made possible to increase the crop productivity per unit land enormously, hence promoting economic development, food for the increasing population and sparing the forests to an extent, which would have otherwise been converted into agricultural land to grow the crops (Foley et al., 2011).

Despite this achievement, Dr. Diouf at the launch of the annual FAO report stated that “far from decreasing, the number of hungry people in the world is currently increasing". This number of hungry people in the world has crossed the one billion mark, of which 642 million live in Asia and the Pacific. Another challenge is to meet the rapidly changing demand of affluent people for quality food with increased nutrient content. According to Indian Government documentation (National Food Security Bill, 2013), "In a recent survey, it was deduced that 22% of the Indian population is undernourished, whereas 40% of children below the age of 3 years are underweight, majority of children aged between 6 to 35 months are anaemic and 33% of the women aged between 15-49 years have a BMI (body mass index, a measure of body fat based on height and weight that applies to adult men and women) below normal. The growth rate and the immunity level of the Indian population have been declining considerably throughout these years." The presented figure is when country grows enough food for its people. There may be many reasons for undernourishment and poverty, the cause of Indian scenario may be argued for lack of warehouse, storage, transportation and above all, lack of will power.

The current world population of 7.1 billion is predicted to attain 9.1 billion mark by 2050, and to nourish the global population food production is needed to be raised by 70 % in developed and double in the developing world (Foley et al., 2011; Mueller et al., 2012). This projected increase in food production will have to overcome ever-escalating energy cost, depletion of underground water, loss of cultivable land to urbanization and salinization, increased drought, flooding, global greenhouse gas emissions and climate change. Undoubtedly, the application of industrially fixed nitrogen fertilizers has revolutionized the productivity, especially of grains worldwide. Indiscriminate use of nitrogen fertilizer has dramatically increased the greenhouse effect, resulting in depletion of stratospheric ozone, formation of smog, contamination of drinking water, acidified rain, and eutrophication of water bodies and stressful ecosystems. The current concentration of nitrous oxide about 310 ppbv is about 10 % higher than the value before this century, while the current rate of increase is about 0.8 ppbv (0.3 %) per year. The values indicate the flow of fixed nitrogen among soils, waterways, oceans, and the atmosphere (Schlesinger, 1997; Socolow, 1999). Too less N means lower crop productivity, poor human nutrition and soil degradation (Sanchez and Swaminathan, 2005),while too much N leads to environmental pollution and its concomitant threats to climate change, agricultural productivity, food security, ecosystem health, human health and economic prosperity. Hence, application of synthetic nitrogen fertilizers must be reduced to protect the environmental degradation caused by agricultural processes. Over 60% of N pollution is estimated to originate from agriculture sector (Bodirsky et al., 2014), hence must be addressed. One of the approaches to improve crop productivity with little N input is to improve the nitrogen use efficiency (NUF) of the crops. The other is to stimulate biological nitrogen fixation. The N_2-fixing organisms convert molecular nitrogen (N_2) in the field, in the soil, near the root system, where it is needed. Biofertilizers not only help to produce more food, but increase soil fertility, save money, time and energy on the mineral fertilizers, and lead to a reduction in greenhouse gas emissions and runoff from fertilizers that pollute various habitats.

Improving the nitrogen use efficiency (NUE)

Nitrogen use efficiency (NUE) can be defined as the ratio of output (harvest as crop products) to inputs (fertilizer, biologically fixed N and N deposition), i.e., (NUE = $N_{\text{yield}}/N_{\text{input}}$) (Bouwman, et al., 2013; Zhang et al., 2015), and has been mathematically defined as: $N_{\text{sur}}=N_{\text{yield}}\{1/\text{NUE}-1\}$, where N_{sur} denotes the difference between inputs and outputs, ($N_{\text{sur}} = N_{\text{input}} - N_{\text{yield}}$), and serves as environmental pollution, while NUE agricultural efficiency and N_{yield} as food security targets (Brouwer, 1998; Zhang et al., 2015). This can predict the potential loss of N to the environment from agricultural soils. However, a fraction of N is recycled within the soil. An improvement in NUE can increase the crop productivity with lesser N input as well as reduce the environmental pollution (Cass man et al., 2003; Davidson et al., 2015). NUE has also been accepted by United Nations General Assembly as an indicator to assess the sustainable development goals (SDSN, 2015). According to Bodirsky et al. (2014) the global agricultural reactive N input should not exceed 50–100 Tg N yr^{-1}, while Zhang et al. (2015) proposed the global limit of 50 Tg N yr^{-1}. To achieve the target by 2050, average global NUE in crop production should be improved from ~0.4 to ~0.7 (Zhang et al., 2015). To realize the goal requires implementation of new technologies, management practices at the farm scale such as slow-release fertilizers and their application via irrigation water, nitrification, urease inhibitors, mixed cropping and government policies.

Biological nitrogen fixation

The habitat of rice paddy and sugarcane fields is optimum condition for N_2 fixing cyanobacteria and *Azolla* (agronomically most important symbiosis). Maximum benefit may be derived by inoculating the fields with competent N_2-fixing cyanobacteria and *Azolla* tolerant to adverse conditions such as drought, radiation, temperature and salinity (Dubey and Rai, 1995; Rai and Rai, 1999; Ladha and Reddy, 2003); by treating seeds with specific bacteria that allow a plant to produce its own fertilizer on its roots, and engineering crops with nitrogen fixation genes (*nif* genes) capable to fix dinitrogen to sustain their growth and yield.

Artificial association of diazotrophs with crop plants-a promiscuous goal

A limited number of prokaryotes are capable to fix dinitrogen and possess *nif* genes (Fig. 1). In the prokaryotes too, this character is not universal. The *nif*genes are present in free-living and symbiotic bacteria, cyanobacteria, and *Frankia*. The free-living diazotrophs are either aerobic such as *Beijerinckia, Spirillum, Derxia* and cyanobacteria, facultative (*Klebsiella, Rhodopseudomonas*) or anaerobic (*Clostridium, Chromatium*). *Azatobacter* and *Azospirillum* are associated with roots of tropical grasses. Endophytic diazotrophs such as *Gluconace to bacter diazo trophicus* and *Herbaspirillum*spp. inhabit the stems and leaves of sugarcane, and *Azoarcus*, the roots of Kallar grass (*Leptochloafusca*). *G. diazotrophicus* colonizes the roots of rice, wheat and other crop plants (Ladha and Reddy, 2003).

Cyanobacteria and symbiotic diazotrophs, *Rhizobium* and *Bradyrhizobium* (forming nodules in leguminous plants) are agronomically much important. *Azorhizobiumcaulinodans* forms N_2-fixing nodules on the roots and stems of the tropical legume *Sesbania rostrata*. In simpler terms, symbiosis between rhizobia and legumes starts with the induction of bacterial *nod* genes and synthesizing nodulation factor (Nod factor) responsible for the developmental changes in the host plant. Cortical cells divide to form the nodule primordia, bacteria penetrate via host-derived infection threads, and invade the plant cell cytoplasm, differentiate into bacteroids and fixes N_2, provide ammonium to the host in return for photosynthates (Broughton et al., 2000; Suzuki et al., 2007). What is needed to understand is the signal exchange between rhizobia and legumes, and the physiological mechanism targeting the maturation and maintenance of the nodules. Inoculation of *S. Rostrata* stems with *A. caulinodans* mutants revealed that the role of many *nif* genes are not identical in different symbiotic systems, while some have no roles at all (Suzuki et al., 2007). Hence, the identification of typical symbiosis-related genes will pave the way in understanding the maturation and maintenance mechanisms of nodules and construct new symbiotic crop systems.

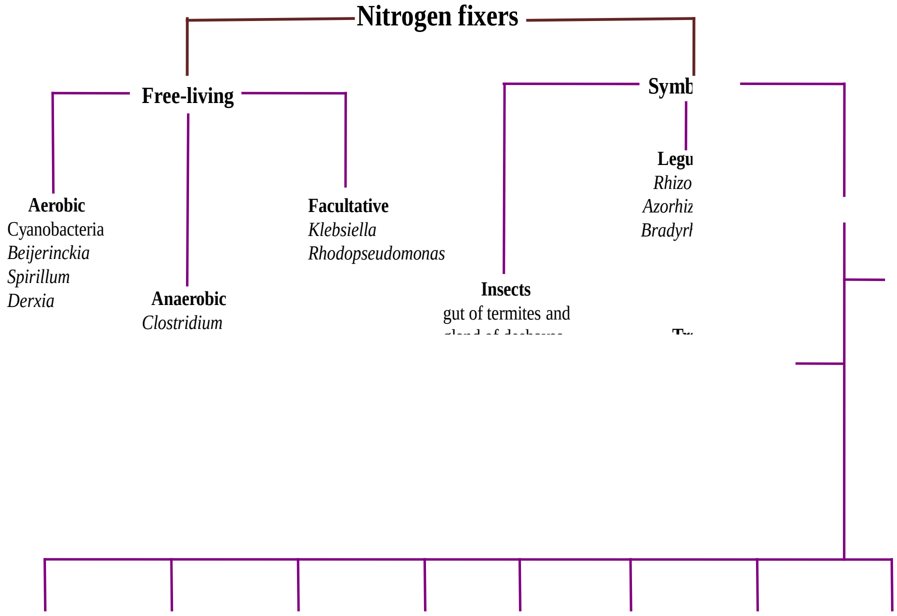

Fig. 1. Free-living and associative molecular nitrogen fixers with representative examples (E, extracellular; I, intracellular).

A critical study of the cyanobiont-host interaction will make possible to understand the complex molecular mechanisms underlying the evolution of obligate endosymbionts. Cyanobacterial symbioses are found with almost all classes of flowering and non-flowering plants and involve taxonomically diverse hosts. *Richeliaintracellularis* and *Calothrix rhizosoleniae* are intracellular cyanobionts in several diatom genera, including *Hemiaulus*, *Rhizosolenia* and *Chaetoceros*. The rates of N_2-fixation are 171–420 times higher under symbiotic state compared to those of the cells living freely, revealing the role of the hosts (diatoms) in the growth and metabolism of cyanobionts (Foster et al., 2011).These intracellular cyanobionts must possess a high degree of regulation and adaptation to maintain the mutualistic symbiosis. These symbioses may serve a key model to study the establishment of nitrogen fixation in eukaryotic hosts and regulation of nutrient exchange.

Lichen *Peltigera* and *Collema* have association with *Nostoc* and *Calothrix* (in cephalodia). In bryophyte *Anthoceros -Nostoc* symbiosis, a set of *Nostoc* spp. genes respond to the chemical signals of *Anthoceros* and form hormogonia, leading to the infection and establishment of the cyanobacterial colony in the plant tissue. The other set of genes respond to the growth conditions in the plant resulting in enhanced heterocyst formation (30-40% compared to only 5–6% in free-living cyanobacteria) and release of some 45–90% of fixed nitrogen to the plant (Chapman and Margulis, 1998; Wong and Meeks, 2002). Liverwort *Blazia* has association with *Nostoc* (open leaf cavity), moss *Sphagnum* with *Haplosiphon* (superficial), the marine sponge L*amellodysideachloroea* with host-specific *Oscillatoria spongeliae*, fern *Azolla* with *Anabaena* (closed leaf cavity), cycads with *Nostoc, Anabaena* (root cortex), and the only angiosperm *Gunnera* with *Nostoc* (in leaf base glands and is intracellular). The intracellular interaction within *Gunnera* and cyanobiont *Nostoc* is unique in flowering plants and may provide an insight to develop novel symbioses between crop plants and cyanobacteria.

Almost all the partners that live in symbioses undergo some morphological alteration (to accommodate the cyanobiont) as well as metabolic adaptations for the exchange of metabolites. In most plant-cyanobacterial symbioses, the infective agents are hormogonia and all host plants produce chemical signals and chemoattractant that trigger their formation and guide them into the plant tissue. The point to be accentuated is that no gene transfer is documented in plant-cyanobacterial symbioses, suggesting less well integration. Secondly, though all cyanobacteria are photoautotrophs, many are facultative heterotrophs, and are not restricted to the areas of the plant that receive light; they can be found in roots, stems, leaves, and thalli. Thus, the promiscuous goal of artificial symbioses is within reach, especially if we consider the ways in which nature has evolved successful systems. Transferring *nif* genes into the plant is to burden them metabolically and energetically, and may not give the desired result in terms of productivity. An option might be to accommodate the cyanobiont by creating specialized structure in the host plant and provide suitable environment (microaerophilic) to interact and accomplish the job of nitrogen fixation and its export.

Approaches

Azotobacter vinelandii mutant with deletion of the *nifL* gene expressed nitrogenase constitutively, and excreted ammonium into the surrounding medium making available to other plants (Bali et al., 1992). The treatment of wheat roots with the synthetic auxin, 2,4-dichlorophenoxyacetic acid (2,4-D) led to the formation of tumour-like structures (para-nodules), which were readily colonized by cyanobacteria (Gantar and Elhai, 1999).

To protect nitrogenase complex from oxidative damage plastids may serve favourable sites. Nitrogenese can be protected from oxygen by functioning in dark;

some cyanobacteria are facultative heterotrophs, while some perform photosynthesis at separate times. Mitochondria may provide low-oxygen environment to allow nitrogenase to function. Moreover, cyanobacteria differentiate heterocysts, which protect nitrogenase against O_2 with no need for the low O_2 tensions maintenance. Furthermore, *Sesbania rostrata* has stem nodules as well as root nodules. Stem nodules are capable of photosynthesis as well as nitrogen fixation. Though challenging, there exists a widespread optimism that recently developed molecular technologies and holistic approaches can allow the substantial impact of biological nitrogen fixation in agriculture.

6. Conclusion

To feed an increasing population of the world, crop production must be increased. Obviously, the limited resources of land and water have already been maximally exploited to meet the demand. Industrially fixed nitrogen has played a significant role in increasing the crop yield, but has exerted significant negative effect on the resources such as energy and its cost, underground water depletion and contamination of drinking water, loss of cultivable land to salinization, and the environment due to greenhouse gas emissions, depletion of stratospheric ozone, eutrophication of water bodies and climate change. Improving nitrogen use efficiency and biological nitrogen fixation are hope to increase crop production with less money, time and energy, reduction in greenhouse gas emissions, runoff from fertilizers that pollute various ecosystems, and thus save the non-renewable resources and the environment. Viable options to achieve the substantial biological N_2-fixation is by inoculating the fields with competent N_2-fixing cyanobacteria and *Azolla* tolerant to adverse conditions, treating seeds with bacteria that allow a plant to produce its own fertilizer, engineering crops (with *nif* genes**),** identification of typical symbiosis-related genes and construct new symbiotic crop systems.

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