Biol Fertil Soils (1999) 28:329–342

REVIEW ARTICLE

B. Mandal · P.L.G. Vlek · L.N. Mandal

Beneficial effects of blue-green algae and *Azolla*, excluding supplying nitrogen, on wetland rice fields: a review

Received: 4 February 1998

Abstract The role of blue-green algae (BGA) and *Azolla* in supplying N to rice fields is well documented. In addition, they also bring about, directly or indirectly, a number of changes in the physical, chemical and biological properties of the soil and soil-water interface in rice fields. For example, BGA liberate extracellular organic compounds and photosynthetic O_2 during their growth, while *Azolla* prevent a rise in the pH, reduce water temperature, curb NH_3 volatilisation and suppress weeds; and both of them contribute biomass. On decomposing, they influence the redox activity and result in the formation of different organic acids in soil. All such changes brought about by BGA and *Azolla* in soil may ultimately influence plant-available nutrients and also soil characteristics. An attempt has been made in this review to highlight these effects of BGA and *Azolla* in rice fields and discuss their possible implications relating to management and productivity of rice-field systems.

Key words *Azolla* · Blue-green algae · Nutrient availability · Wetland rice · Ammonia volatilisation

Introduction

The success of rice production in the tropics and subtropics depends on an efficient and economic supply of N, an element required in the largest quantity in comparison with other essential ones. The use efficiency of N from fertiliser sources in lowland rice is notoriously low, because of its loss from soils through various chemical and biochemical processes. Besides, increasing the application of nitrogenous fertilisers is neither environmental friendly (Conway and Pretty 1988) nor economically viable (Cassman and Pingali 1994). It has, therefore, become necessary to look for alternative renewable resources to meet at least a part of the N demand of rice crops. N-fixing blue-green algae (BGA) or cyanobacteria and *Azolla*, have been shown to be the most important in maintaining and improving the productivity of rice fields (Roger et al. 1993). It has been demonstrated that the N fertility of soil is sustained better under flooded conditions than under dryland conditions (Watanabe and Roger 1984). Favourable conditions for biological N_2 fixation by such BGA is considered to be one of the reasons for the relatively stable yield of rice under flooded condition. Unlike chemical N fertilisers, BGA and *Azolla* neither contaminate the environment nor consume the photosynthates of rice plants (Liu 1979). The importance of N_2-fixing BGA was first recognised by De (1936, 1939) who attributed the self-maintenance of the N status of tropical rice-field soils to the growth of N_2-fixing BGA. Similarly, the fertilising value of *Azolla* in rice fields is well-known and has been utilised over many centuries in China and Vietnam (Watanabe et al. 1981; Lumpkin and Plucknett 1982). The plant-available N of rice soils is increased considerably by the growth of N_2-fixing BGA (De and Mandal 1956; Singh 1961; Stewart et al. 1968) and *Azolla* (Shen et al. 1963; Peters et al. 1977; Singh and Singh 1987). Some excellent treatises on this, both with respect to BGA (Fogg et al. 1973; Roger and Kulasooriya 1980; Venkataraman 1981) and *Azolla* (Watanabe et al. 1981; Lumpkin and Plucknett 1982; IRRI 1987; Wagner 1997) are available.

A yield improvement of rice of between 5% and 25% was found when fields were inoculated with BGA even in the presence of 100–150 kg N ha^{-1} as fertiliser (Sprent and Sprent 1990; Yanni 1992). Since biological N_2 fixation is known to be inhibited by inorganic N, such an observation may imply that BGA confer other

B. Mandal (✉) · P.L.G. Vlek[1] · L.N. Mandal
Department of Agricultural Chemistry and Soil Science,
Bidhan Chandra Krishi Viswavidyalaya, Kalyani 741 235,
West Bengal, India
e-mail: biswa@klyuniv.ernet.in, Tel.: +91-33-826074,
Fax: +91-33-828460

[1] *Present address:*
Institute of Agronomy in the Tropics,
Georg-August University, Goettingen, Germany

benefits besides adding N to the soils. BGA and *Azolla*, in fact, bring about, directly or indirectly, certain changes in the physical, chemical and biological properties of the soil and soil-water interface in rice fields, which are of agronomic importance. The extracellular organic compounds liberated by the algae and the O_2 released due to photosynthesis during their active growth period, and the subsequent addition of biomass after their death, are likely to cause some important changes in the physico-biochemical properties of soils. Prevention of an algae-induced pH rise, reduction in water temperature, curbing NH_3 volatilisation losses and suppressing weeds under *Azolla* cover are also important effects which may cause some benefits to rice cultures. An attempt has been made in this review to collect and collate the little information available on these aspects of BGA and *Azolla* use and discuss their possible implications relating to the growth of rice and sustenance of the productivity of rice fields.

Organic matter content in soil

A build up of organic matter due to algal inoculation in soil was claimed by De and Sulaiman as early as in 1950. Later, a number of workers (Fuller and Roger 1952; Aiyer et al. 1971a; Sankaram 1971; Osmanova 1979; Das et al. 1991) supported the claim with experimental data. A well-developed continuous layer of colonies of different species of BGA in rice fields generally yields a significant amount of biomass. However, wide variations in the reported values of organic C or biomass addition by BGA exist (Table 1). Osmanova (1979) attributed the accumulation of organic matter in takyr soils to the growth of BGA. Using ^{15}N, Nekrasova and Aleksandrova (1982) confirmed that algal biomass contributed significantly to humus formation in soils despite the absence of typical lignin in them. All these results and others compiled by Roger and Kulasooriya (1980) and Roger et al. (1987) indicate that under favourable conditions a good algal bloom in rice fields yields, on average, about 6–8 t of fresh biomass. The persistence of such biomass in soil as organic matter, however, depends on its decomposability. The biomasses of some algae are decomposed quickly, while those of others last longer (Watanabe and Kiyohara 1960). The differing susceptibility of algae to decomposition is related to the relative biodegradability of algal cell-wall compounds, like polyaromatic compounds, (Gunnison and Alexander 1975) and their physiological growth stages. As an example, the decomposability of *Anabaena* sp. in soil is faster than other commonly inoculated BGA species in rice fields. Algal biomass rich in akinetes is also not easily decomposed when compared with algal vegetative cells.

Table 1 Addition of organic C to soils by the growth of blue-green algae (BGA)

Amount (t ha^{-1})	Reference
0.5–1.4	Gollerbach et al. (1956)
6.7	Fuller and Roger (1952)
0.75	Prasad (1949)
0.45	Rao and Burns (1990a)
41.6	Reynaud and Roger (1981)
3.2–6.8	Das et al. (1991)

The enrichment of soil with organic matter due to the incorporation or inoculation of *Azolla* is minimal (Nazeer and Prasad 1984), although a full cover of rice with *Azolla* weighs about 10–20 t ha^{-1}. This is possibly associated with the high decomposability of *Azolla* biomass, since it contains a low amount of lignin ($<5\%$), particularly at a young stage, when it is usually incorporated in to soils. Lales and Marte (1986) observed no significant increase in soil organic matter content in spite of five consecutive crops of rice with *Azolla* on a Maahas clay soil of the Philippines. However, the Chekiang Agriculture Academy (Anonymous 1975) and Singh and Singh (1987) and Sisworo et al. (1990) reported a significant increase in the organic C content in soils due to successive *Azolla* cropping with rice plants. It has been observed that *Azolla* is completely decomposed in soil within 30 days (Kumarasinghe and Eskew 1993). However, if *Azolla* is allowed to mature beyond its linear growth phase – which happens during dual cropping with rice – its lignin content is greatly increased by 30% (Van Hove 1989). Such mature *Azolla* biomass may persist in soils for a longer period, and possibly results in an increase in the organic matter content of soils at a faster rate than is usually seen. However, conclusive evidence on the rate of this build-up and its benefits can be achieved only from a long-term inoculation/incorporation study, because under tropical and subtropical conditions, most of the organic C fixed by BGA and *Azolla* might be lost from the soil as a result of its rapid biochemical oxidation at the high temperatures prevailing during the summer months of the year. Data from long-term experiments with BGA or *Azolla* (Ventura and Watanabe 1993) inoculation are, however, lacking.

Improvement of soil physical properties

In tropical countries after the harvest of winter rice the fields are often used for growing upland crops like maize, potato, wheat, oilseeds, pulses etc. which need good soil physical conditions, particularly a good soil structure, for their growth. At the time of puddling before transplanting rice seedlings, the soil structure is completely destroyed. The inoculation of rice fields with BGA may help to quickly regenerate and improve the soil structure. BGA are known to excrete extracellularly a number of compounds like polysaccharides, peptides, lipids etc. during their growth in soils (Marathe 1972; Mehta and Vaidya 1978; Bertocchi et al. 1990). These compounds possibly diffuse around soil particles and hold/glue them together in the form of microaggregates. Besides, these compounds, particularly polysaccharides, are made of fibres which can also entangle clay particles and form clusters. These clusters or microaggregates, in turn, grow and take the shape of macroaggregates and subsequently of larger soil aggregates. The interwoven nature of growing algal filaments may also help in binding the soil particles along with the organic C added through algal biomass. The importance of these compounds in soil-aggregate formation or soil stabilisation has been indicated by many workers (Schulten 1985; Rogers et al. 1991; Rogers and Burns 1994). Some researchers, however, have considered polysaccharides as transient adhesives (Tisdall and Oades 1982) and/or not directly involved in the formation of aggregates (Martens and Frankenburger 1992), although the products of their microbial degradation like aliphatic and polyphenolic compounds are considered to be responsible for this (Haynes et al. 1991). The quantity and quality of the excreted compounds also vary depending on the species of BGA, their physiological growth stages and also the associated environmental conditions (Mehta and Vaidya 1978; Lama et al. 1996). Some species give low yields of excreted compounds (e.g. *Anabaena*), while others give high yields (e.g. *Gloeotrichia*). Such polysaccharides or extracellular mucilages of BGA can account for as much as 44% of their dry weight (Moore and Tischer 1964). Polysaccharides from different algal species also differ with respect to their protein, uronic acid and sugar compositions (Bertocchi et al. 1990), and thus in their stability in soils with respect to microbial and thermal degradation.

Burns and his co-workers (Rao and Burns 1990b; Rogers and Burns 1994) observed significant increases in the values of soil aggregate stability (measured as the resistance of aggregates to degradation during wetting and physical disruption) due to an increase in the polysaccharide content of soils as a result of algal inoculation. Similarly, water-stable aggregates, which are an intregal part of good (soil) aggregate formation, have also been shown to increase significantly due to algal inoculation, resulting in an improvement in the water-holding capacity and aeration status of soils (Singh 1961; Marathe 1972; Subhashini and Kaushik 1981; Roychoudhury et al. 1983; Tiwari et al. 1991). Further, Singh (1961) reported that the mucilaginous and fragile thalli of *Aphanothece* sp. formed a compact grey substratum firmly holding the soil particles together which checked both wind- and water-mediated soil erosion, particularly in light and sandy soils subjected to heavy grazing. Such improvement in soil aggregation due to algal inoculation ultimately favoured better seedling emergence of upland crops sown after the paddy harvest (Rogers and Burns 1994). All these results apparently suggest that the algal species which liberate higher amounts of complex and thermostable polysaccharides will possibly be a better choice for inoculation in rice fields for the regeneration of the soil structure. However, such algal species are known to be less efficient N_2 fixers.

Table 2 Physical and chemical changes in soil after inoculation with the BGA *Nostoc muscorum*. *LR* Low rate, *HR* high rate source: Rogers and Burns (1994)

	Aggregate stability	Total organic C (mg g^{-1} soil)	Carbohydate C (μg g^{-1} soil)	C:N ratio
Non-inoculated soil	68.0	22.4	3.9	18:1
Inoculated with LR	80.0	33.7	13.8	12:1
Inoculated with HR	80.2	36.6	11.8	14:1

Use of *Azolla* as green manure is also reported to improve soil physical properties by increasing the porosity (3.7–4.2%) and decreasing the specific gravity of soils (Anonymous 1975). Long-term plots at IRRI have shown that the bulk density of the soil decreases with continued *Azolla* use (Kumarasinghe and Eskew 1993; Ventura and Watanabe 1993). These changes in soil properties are important, since they reduce the amount of energy required to work the soil and improve water infiltration, aeration and soil temperature. These effects of BGA and *Azolla* are more relevant to wetland rice soils where structure and other physical properties are destroyed by puddling before transplanting of rice seedlings. Such effects of BGA and *Azolla* in regenerating the physical properties of puddled soils have a special significance where rice is followed by an upland crop like maize, potato etc. which need a good tilth. Very little research has so far been done on these aspects. However, as mentioned earlier, whatever the quantity and quality of polysaccharides of BGA and amount of biomass added through *Azolla*, perceptible changes in the physical properties of soil may be achieved only from the implementation of long-term algalization and/or azolliculture programmes.

O_2 concentration and associated changes

BGA are aerobic photosynthetic organisms. In the medium of their growth, they release a lot of O_2 during photosynthesis through photosystem II. As a result, when they grow in rice fields they make the standing water highly oxygenated (Harrison and Aiyer 1913). The concentration of O_2 in rice-field floodwater normally varies around 4–6 μg g^{-1} (Mandal 1961; Saito and Watanabe 1978; Kröck et al. 1988a). When there is a profuse growth of BGA, the O_2 concentration sometimes reaches 10–12 μg g^{-1} (Mandal 1961; Lakshmanan et al. 1994), and the surface layer of the soil absorbs enough O_2 through diffusion to become aerobic in nature and, therefore, prevent the development of highly reduced conditions underneath it. This is an important benefial effect in areas where rice is grown continuously throughout the year under flooded conditions in soils with relatively high organic matter contents. In these areas, continuous waterlogging creates intense reducing conditions with redox potential values falling below –200 mV (Ponnamperuma 1972). These conditions favour the formation and subsequent accumulation of a high amount of harmful oxidizable organic matter, a large quantity of Fe^{2+} and also S^{2-}, which sometimes reach toxicity levels for rice plants (Aiyer et al. 1971a,b). Inoculation of rice fields with BGA under such conditions may be helpful in regulating the formation of such toxic substances by maintaining the redox potential at a relatively high level. In fact, Aiyer et al. (1972) reported a significant reduction in the oxidizable organic matter, total S^{2-} and Fe^{2+} content of soils after four successive rice crops with BGA inoculation. A high O_2 tension in the soil, arising from algal photosynthesis, seems to facilitate the oxidation of these reduced components. A few other researchers (Saha and Mandal 1979; Das et al. 1991) also reported a significant reduction in the water-soluble and exchangeable Fe and Mn contents in soils due to inoculation with BGA. The transformation of Fe and Mn in soils on algal inoculation is discussed later in more detail.

As mentioned above, the establishment of a comparatively thick aerobic layer on the surface due to algal growth and the existence of an anaerobic, reduced layer below provide a highly favourable environment for the nitrification-denitrification processes to proceed. When applied or native NH_4^+-N in soil comes into contact with this oxygenated surface layer, it is converted to NO_3^--N, which on diffusion to the anaerobic layer is subjected to the process of denitrification by denitrifiers and is lost as gaseous N. Besides this, the rice rhizosphere itself is oxygenated due to the transport of O_2 from the atmosphere to the soil through the aerenchyma (John et al. 1974), while the surrounding zone lacks O_2, thus making the environment highly favourable for nitrification-denitrification (Garcia and Tiedje 1982). Therefore, the extra O_2 received in the system from BGA makes the conditions more favourable for the denitrification loss of the energetically costly N input. On the other hand, it leads to the oxidation of the Fe^{2+}, which sometimes occurs in the rice rhizosphere at a very high concentration, and precipitates it as FeOOH forming a reddish coat on roots which may constitute up to 14% of the root dry weight (Chen et al. 1980). Fe^{3+} and Fe^{2+} may have an inhibitory effect on denitrification in the rice rhizosphere, since these ions have shown some inhibitory effects on denitrification in laboratory studies (Komatsu et al. 1978). However, if denitrification occurs at sites away from the rhizosphere the inhibitory effects of Fe may be insignificant. However, the relative importance of these factors with respect to denitrification has yet to be properly assessed. If the O_2 released by BGA accelerates N loss through denitrification, this may be more than compensated for by the beneficial effects of BGA through N accretion. Detailed studies should, therefore, be undertaken to ascertain the possible role of BGA in such processes in rice fields.

The growth of *Azolla* in rice fields also causes changes in the composition of floodwater and the soils underneath owing to variations in the light-transmission ratio (LTR) and photosynthetic activity. Kröck et al. (1988a) observed a drop in the O_2 concentration and pH to the extent of 3–8 $\mu g\ g^{-1}$ and 1.4 units, respectively in rice-field floodwater due to *Azolla* growth. Such changes may also affect N transformation in soils. Denitrification may be reduced by the *Azolla* cover due to a thinner oxidised soil layer, a consequence of the lower O_2 concentration in floodwater and decreased oxidation of NH_4^+ to NO_3^- at lower pH values (Focht 1979) and O_2 concentrations. The existence of a close relationship between the pH of soil and floodwater and N loss by NH_3 volatilisation is well established (Vlek and Craswell 1979; Fillery and Vlek 1986). *Azolla* cover is, therefore, expected to reduce N loss by volatilisation also. This is discussed later in greater detail. Through these changes, *Azolla* may help in reducing N loss from rice fields and thus promote the N-use efficiency of rice. Very little research has so far been done to examine this.

NH_3 volatilisation

As mentioned earlier, the efficiency of N when applied in the form of urea to flooded rice is very low because of its loss through various mechanisms, including NH_3 volatilisation. Such loss of N through NH_3 volatilisation sometimes accounts for as high as 50% of the applied urea within 2 weeks of its application, depending on fertiliser management and environmental conditions (Fillery and Vlek 1986). NH_3 volatilisation is a function of the partial pressure of NH_3 (pNH_3) in the floodwater, which in turn is determined by the total

Table 3 Effect of algal inoculation on soil properties related to redox system in soil

Soil property	Without algae	With algae	Increase or decrease	CD 5.0%
Total N (%)	0.1	0.098	−0.002	NS
Organic C (%)	0.98	1.125	+0.145	NS
Oxidisable organic matter[a]	2.97	2.48	−0.49	0.1
Total sulphide ($\mu g\ g^{-1}$)	12.2	9.2	−3.0	1.2
Fe^{2+} ($\mu g\ g^{-1}$)	34.3	28.7	−5.6	3.0

[a] In ml of 0.01 N $KMnO_4$ solution per 25 g of soil source: Aiyer et al. (1972)

$(NH_3+NH_4^+)$-N level, pH and temperature of the floodwater and also the ambient wind velocity (Vlek and Craswell 1981). pNH_3 increases ten fold for every unit increase in pH and also significantly with an increase in temperature. Therefore, any agent which can influence the pH and temperature of floodwater in rice fields may accelerate or decelerate this process accordingly. Urea, when applied to flooded rice fields, turns the floodwater alkaline upon hydrolysis to $(NH_4)_2CO_3$, an alkaline salt. In addition, aquatic plant communities also stimulate the loss of NH_3 from flooded soils by their photosynthetic activity through consumption of dissolved CO_2. Diurnal fluctuations in floodwater pH from near neutral to as high as 10 are common in rice fields where algae, particularly green algae are active, and accelerate NH_3 volatilisation (Vlek and Craswell 1981; Fillery et al. 1985; Bowmer and Muirhead 1987). Algal blooms, mostly green, rapidly develop upon N fertilisation of flooded rice (Watanabe et al. 1977), but die off once light penetration is limited by the rice canopy. The decay of green algae might be accelerated when *Azolla*, grown in association with rice, shades out the algae. Growing *Azolla* can act in a number of ways to curb NH_3 volatilisation loss from rice fields. *Azolla* may: (1) form a physical barrier to the escaping NH_3, (2) intercept the incoming light which is necessary for prolific algal growth, (3) absorb a high amount of NH_3 or NH_4^+, temporarily storing it for future release, (4) exude protons while absorbing NH_3, (5) increase the pCO_2 of floodwater by respiration, which subsequently decreases floodwater pH etc. (Vlek et al. 1992, 1995; Kumarasinghe and Eskew 1993; Sisworo et al. 1995). The cyanobiont *Anabaena-Azolla* also helps in this process by driving C (Tel-Or et al. 1991) from *Azolla* (not from floodwater, like other green algae) and fixing N without increasing the floodwater pH. Experimental evidence in support of these hypotheses are available. Prevention of an algal-induced pH rise (Kröck et al. 1988a; Sisworo et al. 1995; Vlek et al. 1995) and a reduction in floodwater temperature and LTR under *Azolla* cover (Kröck et al. 1988b) are well documented. These effects of *Azolla* cover on NH_3 volatilisation loss in rice fields might help to explain the observed increase in N use efficiency of rice in field experiments co-ordinated by the International Atomic Energy Agency in various countries (Kumarasinghe and Eskew 1993, 1995). Their N uptake data showed that urea-N was more efficiently used by a mixed *Azolla*/rice crop when compared to a rice monoculture, increasing the N recovery by 10%, 60% and 53% in China, Sri Lanka and Thailand respectively. The presence of an *Azolla* cover, in fact, reduced NH_3 volatilisation by 20–50% of that measured in the absence of *Azolla* (Villegas 1985). Also, Vlek et al. (1992), in a preliminary study, showed a reduction in N loss from 80% of applied urea in the absence of *Azolla* to 10% and 35% for 20 and 40 kg N ha^{-1} fertilizer rates, respectively, when an *Azolla* mat was present. Subsequently, in a definitive study with ^{15}N, Vlek et al. (1995) showed that a full cover of *Azolla* could significantly reduce losses of applied urea-N, i.e. from 45% and 50% loss to 20% and 13% loss for the 30 and 60 kg N ha^{-1} treatments, respectively. By comparing the relative importance of the different mechanisms, as mentioned earlier, they could show that one-quarter of the applied N was tied up in the *Azolla* biomass, and that the reduction in NH_3 volatilisation was largely related to the depression by *Azolla* of the floodwater pH. They also concluded that the benefits of *Azolla*, even when present in small quantities (200–500 kg fresh material ha^{-1}), in conserving basal urea-N, outweighed its competition for the applied N with growing rice. The urea-N conserved by *Azolla* may be as important as its biologically fixed N. Identification of the relative efficacy of different species of *Azolla* in this regard may be useful with respect to the future adoption of management programmes for the field which incorporate this genus.

Transformation of soil P

BGA, like P-solubilizing bacteria, are known to have the ability to mobilise bound phosphates. They have been shown to solubilise insoluble $(Ca)_3(PO_4)_2$ (Bose et al. 1971), $FePO_4$ (Wolf et al. 1985), $AlPO_4$ (Dorich et al. 1985) and hydroxyapatite ($Ca_5(PO_4)_3.OH$; Cameron and Julian 1988) in soils, sediments or in pure cultures. There are mainly two hypotheses, proposed by two groups, to explain how BGA solubilise such bound phosphates. One group suggested that they might syn-

Table 4 Reduction in loss of applied urea-^{15}N due to *Azolla* cover of floodwater after 7 weeks of rice growth

Cover	Fertiliser rate (kg N ha^{-1})	N uptake rice (%)	N uptake *Azolla* (%)	Soil N (%)	N loss (%)
None	30	43.8	–	6.0	50.2
	60	42.8	–	7.6	49.7
Styropor	30	50.7	–	11.6	37.8
	60	55.4	–	6.6	38.0
Azolla	30	52.1	23.5	3.4	21.0
	60	57.5	23.5	6.1	13.0

Source: Vlek et al. (1995)

thesise a chelator (chelators?) for Ca^{2+} and drive the following dissolution reaction to the right without changing the pH of the growth medium (Cameron and Julian 1988; Roychoudhury and Kaushik 1989):

$$Ca_{10}(OH)_2(PO_4)_6 = 1\,OCa^{2+} + 2\,OH^- + 6\,PO_4{}^{3-}$$

Others (Bose et al. 1971) were, however, of the opinion that H_2CO_3 and other organic acids released by BGA during their growth could solubilise P from Ca sources following the reaction:

$$Ca_3(PO_4)_2 + 2\,H_2CO_3 = 2\,CaHPO_4 + Ca(HCO_3)_2$$

A third group (Arora 1969; Saha and Mandal 1979; Mandal et al. 1992a) believed that the above mechanisms operate simultaneously. Once solubilised, the $PO_4{}^{3-}$ is taken up by the growing algal cells for their nutrition. After completing their growth cycle, when the cells undergo lysis the cell-bound $PO_4{}^{3-}$ is released in the growth medium and becomes available to plants on mineralisation. Observance of an initial decrease in the available-P content in soils due to algal growth and an appreciable increase later during biomass decomposition (Saha and Mandal 1979; Mandal et al. 1992a) supported this possible pathway. In an in-depth study, Mandal et al. (1992a) showed that growth of a mixture of BGA (*Anabaena*, *Nostoc*, *Cylindrospermum* and *Tolypothrix* spp.) in soils caused an increase in organic P with concomitant decreases in Olsen-P, Al-P, Fe-P and Ca-P, but with little changes in reductant-soluble Fe-P and occluded Al-P fractions. When this algal biomass was incorporated into the soils, there was an increase in Olsen-P with a simultaneous decrease in all the other P fractions, including organic P. P assimilated by BGA and incorporated into their cells during growth is released upon bacterial decomposition in the form of soluble organic P compounds (sugar-P, lipid-P, nucleic- and nucleotide-P etc.) or condensed polyphosphates (Thompson et al. 1994). These compounds are later mineralised or hydrolysed to orthophosphates resulting in an increase in available (Olsen) P in soils. Further Arora (1969) opined that the organic P of nucleic acids, nucleotides etc. of the algal materials may become plant-available due to dephosphorylation during the growing season of crops. Release of algal cell P is, however, controlled by temperature, pH and ionic strength of the medium. The released P is again partly condensed as polyphosphates (Bortoletti et al. 1978), which are known to have less reactivity and, therefore, may remain in plant-available forms in soils for a longer time. One important point, however, drawn from these results is that plants may experience temporary deprivation of, or at least competition for, the P they require, particularly during their early growth period, due to algal inoculation.

Decomposition of the algal biomass also intensifies the reducing conditions of soil (Saha et al. 1982) and stimulates the reduction of Fe^{3+}-P to the more soluble Fe^{2+}-P. This also results in the formation of various organic compounds which have chelating properties, which may form chelates with Al and Fe and thus release P from Al- and Fe-bound forms. Inoculation with BGA may, therefore, be useful in making bound P available to plants. When P in the form of water-soluble fertiliser is applied to soils, particularly lateritic ones rich in Fe and Al, it gets quickly converted to its insoluble forms, such as $FePO_4$, $AlPO_4$, $Ca_3(PO_4)_2$, $Ca_5(PO_4)_3.OH$ etc., and becomes unavailable to plants. The solubilising effects of BGA may lead to their reconversion into available forms.

The solubilising effect of BGA on bound $PO_4{}^{3-}$ may also be used for the efficient utilisation of low cost, low grade (in terms of P content) rock-phosphate fertilisers where $PO_4{}^{3-}$ remains bound as various forms of apatite, like hydroxyapatite, carbonoapatite, choloroapatite etc. These rock phosphates are generally used in acid soils as P fertiliser. It is possible that if rock phosphate is used with BGA inoculation in acid soils, its efficacy as a source of P may be increased. In fact, Roychoudhury and Kaushik (1989) reported increased solubility of P in rock phosphate (Mussorie) due to its inoculation with BGA. Pal (1983) also observed a greater solubilisation of P from rock phosphate treated with BGA in an acidic soil (pH 5.2).

Fuller and Roger (1952) observed a greater uptake of P by plants from algal materials than from inorganic phosphates when applied in equal amounts. They concluded that: (1) P in algal material is more available to plants than inorganic phosphates over longer periods, (2) chemical fixation is not so important a factor with respect to algal material as with respect to inorganic phosphates, and (3) temporary conversion of available soil or fertiliser P into cell materials by soil algae may be a desirable process from the stand-point of long-term availability. Their proposed hypothesis was that soil algae removed available P from the sphere of chemical fixation by converting it into cell materials or by absorbing it in "luxury" amounts that might be released gradually for crop use through the process of exudation, autolysis or microbial decomposition of old algal cells. Algae also have long been known to take up P in excess of their immediate needs, which may subsequently be released in the form of dissolved organic P (Lean and Nalewajko 1976).

Like BGA, the incorporation of *Azolla* in to rice fields also increases P availability in soils (Singh et al. 1981; Saha et al. 1982; Singh and Singh 1987; Nagarajah et al. 1989). This has been attributed to the decomposition of *Azolla*'s biomass, rich in organic forms of P, and the subsequent release of P in the form of available P. Other possible mechanisms for increased P availability in soils on the decomposition of *Azolla's* biomass may be reduction and chelation. Increased availability of P in soils on the incorporation of *Azolla* ultimately increases the uptake of P by rice plants (Singh and Singh 1987) and their P concentrations.

Using ^{32}P, Sampaio et al. (1984) indicated that P contained in *Azolla* was, like algal P, much more available than P in $Ca(HPO_4)_2$, which is the main compo-

Table 5 Changes in available P (μg g^{-1}) in soils due to incorporation of BGA, *Azolla* and urea

Days of flooding	Control	BGA	*Azolla*	Urea
7	7.5	7.92	9.37	9.08
14	3.58	3.94	4.89	4.48
21	5.32	13.55	13.97	6.29
28	6.97	14.06	18.45	7.90
35	7.45	10.89	11.62	7.85

Source: Saha et al. (1982)

nent of the commonly used P fertiliser, triple superphosphate. Calculating from their (Sampaio et al.) data, Kumarasinghe and Eskew (1993) indicated that *Azolla*-P was about 100 times more available than that in triple superphosphate fertilizer. Hirimburegama et al. (1995) subsequently using ^{32}P, reported that the availability of *Azolla*-P to rice is similar to that from super phosphate fertiliser. Thus, although the expected amount of P contained in *Azolla* is, at most, 6 kg ha^{-1} (taking 0.4% as the average P and 15 q ha^{-1} dry biomass production), it could have a significant effect on the growth of rice. This becomes even more likely when one considers the fact that *Azolla* responds very significantly to added P in terms of its growth and increase in its acetylene-reducing activity (Tung and Shen 1981; Watanabe 1987). Now, if *Azolla* were fed with higher amounts of P (which need to be added to rice and its succeeding crop, in particular) it may make the element more available to the crops and lead to increased N fixation. It has been observed that *Azolla* can be preloaded with P up to its maximum luxury uptake level thus attaining 1.0–1.6% P (dry weight) as compared with a normal concentration of about 0.4–0.5% P (dry weight) (Diara et al. 1987).

Transformation of Fe, Mn, Zn and Cu

BGA, as mentioned earlier, liberate O_2 and also various kinds of organic compounds, including organic acids, as extracellular products (Watanabe 1951; El-Essawy et al. 1985; Vorontsova et al. 1988; Kerby et al. 1989). Many of them can form chelates with micronutrients like Fe, Mn, Zn, Cu etc. (Das et al. 1991, 1995; Mandal et al. 1992b). BGA also cause diurnal fluctuations in soil and floodwater pH (Fillery et al. 1985; Roger 1996) through utilisation of dissolved CO_2 in the floodwater for photosynthesis during the day and release of CO_2 into the floodwater by respiration during the night. After completion of the growth cycle, the algal biomass undergoes anaerobic decomposition in rice soils resulting in the formation of various organic acids, causing a decrease in the Eh values of the soils (Saha et al. 1982). All these changes are likely to affect the transformation and availability of micronutrients, particularly the redox elements, viz Fe and Mn, in soils. Significant decreases in the water-soluble and exchangeable Fe and Mn contents with concomitant increases in their higher oxides (bound forms) in soils due to the growth of BGA have been reported (Saha and Mandal 1979; Das et al. 1991) Subsequent in situ decomposition of the algal biomass, however, reversed the transformation. The diethylene triamine penta acetic acid (DTPA)-extractable (considered to be plant-available) Fe content in soils also decreased during the growth of algae, followed by an increase during their subsequent decomposition (Pal 1983). A higher O_2 concentration in floodwater and associated soil environment in the presence of BGA prevents the development of highly reduced conditions and slows down the rate of conversion of Fe and Mn from their higher-valent (Fe^{3+}, Mn^{4+}) to lower-valent (Fe^{2+}, Mn^{2+}) forms; while the anaerobic fermentation of algal biomass in submerged soils leads to the formation of various organic compounds which convert insoluble Fe compounds into water-soluble forms. Besides, decomposition of algal biomass results in the release of electrons which increase redox activity, thus facilitating the reduction of Fe^{3+} and Mn^{4+} compounds to more soluble Fe^{2+} and Mn^{2+} forms. Such changes in the concentration of Fe and Mn in soils during growth and subsequent biomass decomposition of BGA may help to alleviate Fe toxicity to young rice plants in organic-matter-rich acid soils and to meet their increased Fe demand at the maximum vegetative growth stage (Das et al. 1991). An initial high concentration of Fe in these soils may also enhance the establishment of BGA (Mahasneh and Tiwari 1992).

Sajwan and Lindsay (1986) and Dutta et al. (1989) have suggested that increased solubility of Fe depresses Zn^{2+} solubility through the formation of $ZnFe_2O_4$ or similar franklinite-like solid materials. A decreased content of the readily available form of Fe in soil due to the growth of BGA may be helpful in minimising Zn deficiency in rice, at least during early growth stages (Mandal et al. 1992b). Das et al. (1995) also observed an increased availability of Zn and Cu in soils inoculated with BGA. Inoculation with BGA can thus help to regulate the concentrations of Fe and Mn, and also Zn, in organic-matter-rich acid soils on flooding to the benefit of the growing rice plants.

Incorporation of *Azolla* as green manure (GM) also influences the transformation and availability of Fe, Mn, Zn, Cu etc. in flooded rice soils (Nagarajah et al. 1989; Mandal et al. 1997). An increase in the concentration of native Fe and Mn, but a decrease in that of Zn and Cu, in soil solution were observed when *Azolla* was incorporated as GM (Nagarajah et al. 1989). The recovery of fertiliser Zn and Cu in DTPA-extractable forms also decreased in flooded lateritic soils with *Azolla* as GM, owing to increases in the partial pressure of CO_2 and pH of the soils, although the possibility of microbial immobilisation of the nutrients cannot be ruled out. As time progressed, however, the decrease in the DTPA-extractable forms disappeared, and an increase in the recovery of the added Zn and Cu was recorded. It was found that the decrease persisted longer and was

Table 6 Changes in different forms of Fe and Mn (μg g^{-1}) in soils due to the growth of BGA for 60 days

Forms of Fe and Mn	Fe		Mn	
	Without algae	With algae	Without algae	With algae
Water-soluble and exchangeable	16.7	13.6	33.1	29.1
Organically bound	654	683	68.9	74.2
Easily reducible	321	319	27.8	32.2
Amorphous oxides (bound)	3776	4009	47.9	52.2
Crystalline oxides (bound)	10621	10766	46.6	48.9

Source: Das et al. (1991)

more acute with *Azolla* than with *Sesbania* treatment because the former had a higher content of lignin which decomposes rather slowly (Mandal et al. 1997). The Zn use efficiency of rice when this element is added to red and lateritic soils may be increased by preflooding, which lowers the soils' Zn-fixing capacity (Mandal et al. 1992c). However, when *Azolla* vis-à-vis *Sesbania* is to be applied as GM to such soils, the duration of the preflooding period needs to be prolonged. Another important aspect of *Azolla* observed by Johal (1986) was that rice plants grew better and more harmoniously in response to micronutrients (Fe, Mn, Zn, Cu and Co) supplied through *Azolla*, whereas mineral salts providing the same concentrations of micronutrients as supplied by *Azolla* proved toxic to the rice crop.

Amelioration of saline and sodic soils

Saline and sodic soils constitute a large area of agricultural land in the world. Besides, a good part of prime agricultural land becomes saline every year due to poor and faulty management /irrigation practices (Richards 1995). Sodic soils have a high pH, high exchangeable Na, measurable amounts of carbonates and undergo extensive clay dispersion (deflocculation, due to the high zeta potential of active Na^+), leading to poor hydraulic conductivity and reduced soil aeration; while saline soils contain excess amounts of soluble salts imparting high osmotic tension to plant roots for absorption of water and nutrients. Primarily, the reclamation of sodic soils requires the replacement of exchangeable Na with Ca. This is normally done by the application of suitable soil amendments, like gypsum, followed by leaching. The improvement of saline soils, on the other hand, requires leaching of excess soluble salts from the rhizosphere by good quality water. Reports of biological reclamation of these soils through the use of BGA are available (Singh 1950; Kaushik 1989). These methods of reclamation were possibly based on the observations of extensive growth of BGA on alkali or "usar" soils of India (Singh 1950) and on the salted "takyr" soils of the USSR (Gollerbach et al. 1956). These observations indicated a considerable tolerance of BGA to salinity and/or alkalinity stress. Several physiological mechanisms underlying such tolerance have now been identified. Curtailment of Na^+ influx (Apte et al. 1987) and accumulation of inorganic (K^+ ion) or organic (sugar, polyols and quaternary amines etc.) osmoregulators (Blumwald et al. 1983; Reed et al. 1984) are the important mechanisms that provide adequate protection to BGA against such salt/sodicity stress. BGA exposed to such salinity/sodicity stress may lose or have diminished nitrogenase activity due possibly to the diversion of their cellular energy towards the biosynthesis of osmoregulators (Apte et al. 1987). In such cases, the addition of a few kilograms of N, particularly as NO_3, per hectare together with algal inoculation has been shown to be very effective in protecting them from these stresses and allowing them to establish in the stressed environment, and subsequently enhances their potential as N biofertilizer (Reddy et al. 1989; Fernandes et al. 1993). Once established and subsequently acclimatised to the stress, they may act in ameliorating their surrounding environment. Singh (1961) observed in laboratory experiments over a 3-year period a significant improvement in soil properties of saline-alkali soils after algal growth compared with the control covered with a black cloth. The soil pH decreased from 9.2 to 7.5 along with large increases in organic matter content (69%), total N (46%), water-holding capacity (35%), exchangeable Ca (31%) and different forms of P. A reduction in electrical conductivity, exchangeable Na and soil pH (Kaushik et al. 1981; Kaushik and Subhashini 1985) and an increase in the soluble Ca and Mg content of soils (Jain and Kaushik 1989) have also been reported due to such algalization. The increase in soluble Ca and Mg and decease in exchangeable Na may ultimately lower the sodium adsorption ratio – an index of alkalinity in soil – of the soils and thus alleviate the negative effects of high sodicity. In fact, Kaushik and his co-workers (Kaushik and Krishna Murthi 1981; Subhashini and Kaushik 1981) observed a considerable increase in the hydraulic conductivity of sodic soils due to BGA inoculation and found that it compared favourably to the use of gypsum in such soils.

A significant reduction in soil salinity (12–35%) due to repeated cultivation of *Anabaena torulosa* in soils rendered saline owing to bad farm management, has also been reported (Thomas 1977). The rice yield in saline soils is also less affected when N is given in the form of algal inocula vis-à-vis urea (Antarikanonda and Amarit 1991). Further, such algal inocula have proved to be almost equally effective in increasing the rice yield in saline soils when compared with gypsum and/or pyrite treatments (Sharma et al. 1989; Kaushik 1994). Even when irrigated with saline water, BGA inoculation was found to be useful in minimising the deleterious effect of the increased salinity on the barley crop (Jain and Kaushik 1989).

However, Rao and Burns (1991) opined that the then current arguments favouring BGA as a biological amendment for the reclamation of alkali soil, in particularly, were untenable. In a highly alkali soil inoculated with a mixture of seven species of BGA for 11 and 17 weeks they observed no significant changes with respect to the control in hydraulic conductivity, pH, exchangeable Na, exchangeable Ca and exchangeable Na percentage – whose changes are the essential requirements for alkali soil reclamation. Neither did Bhardwaj and Gupta (1971) find any appreciable improvement in an alkali soil with repeated cultivation of BGA (*Nostoc* sp.) for 4 months in a field trial.

In an alkali soil almost all the problems with respect to rice cultivation are associated with the high concentration and/or activities of Na^+. If somehow its activity is checked, the whole problem is solved. BGA are quite tolerant to high alkalinity and can take up appreciable amounts of Na (although disagreement exists regarding their high Na^+ absorption capacity; Apte and Thomas 1986) (Subhashini and Kaushik 1981; Roychoudhury et al. 1985). They secrete organic acids, particularly under salt stress (Singh 1961; Sprent and Sprent 1990) which can act on $CaCO_3$ to dissolve Ca. They also excrete a number of biologically active compounds, i.e. bioflocculants (Jha et al. 1987; Levy et al. 1992), which can flocculate the dispersed clay particles in alkali soils by inactivating/scavenging Na^+. All these effects of BGA may at least temporarily cause inactivation of Na^+ in alkali soils and make the soil environment favourable to the growth of plants. Successive cultivation of BGA makes the environment more favourable and after a few years it may help to produce a reasonably good yield of crops, as observed by Singh (1961) for sugarcane after 3 years of reclamation with BGA. Although such biological soil amelioration is a time-consuming process, it is considered to be a sustainable approach as compared to reclamation by chemical amendments (Oikarinen 1996). What is needed, is to improve the reclamation technique with BGA by integrating its application with the use of a few hundred kilograms of gypsum per hectare (excess Ca also depresses algal growth!) and selection of a suitable profusely growing and alkaline- and/or saline-tolerant species of BGA viz *Nostoc commune, Anabaena torulosa, Westiellopsis prolifica* etc. Besides, there is a good possibility of the use of genetically manipulated species of BGA tolerant of high salinity or high alkalinity for such reclamation in the near future, since a few strongly alkaliphilic and saline-tolerant species have already been engineered (Apte and Haselkorn 1990; Singh et al. 1991 1996*)*. Detailed feasibility studies may be initiated to this end using these engineered species in order to develop a low cost and sustainable technology for the amelioration of saline/sodic soils.

Weed control

The cost of controling weeds in rice fields sometimes constitutes as much as 20–25% of the total cost of the cultivation of rice (De Datta 1981). If *Azolla* and BGA are inoculated into rice fields and they grow profusely, the cost of weeding may be minimised. They can act as weed suppressers, particularly of submerged photosynthetic weeds, since algal blooms and/or an *Azolla* mat covering the floodwater surface of rice fields reduces weeds′ photosynthetic activity by intercepting light and thus significantly depresses their growth. This beneficial effect of *Azolla*, in particular, was noticed during the early part of this century (Braemer 1927). Subsequently, a number of researchers reported this benefits of *Azolla* (Janiya and Moody 1981, 1984; Kannaiyan et al. 1983; Satapathy and Singh 1985; Kröck et al. 1988c; Van Hove 1989). Ngo (1973), while recording the suppressive effect of different mat densities of *Azolla pinnata* on the quantity of *Echinochloa crusgalli*, observed that after a 6-week period the 50% *Azolla* cover plot had a 70% reduction, and the 100% *Azolla*-cover plot a 93% reduction in the *Echinochloa crusgalli* population compared to the control. Rains and Tally (1979) reported that early development of *Azolla filiculoides* eliminated *Cyperus difformis* and *Polygonum* species from the paddy fields, but not E. *crusgalli.* Similar suppressive action of *A. pinnata* on the growth of the former two weeds and also on *E. crusgalli*, *Cynodon dectylon* and *Ludwigia parviflora*, but little effect on *Scirpus articulatus* and *Marsilea quandrifolia* as well the algae *Spirogyra* sp. and *Chara* sp., in rice fields was observed by Satapathy and Singh (1985). These results indicated that *A. pinnata* is more effective than *A.* f*iliculoides* in suppressing the growth of *E. crusgalli.* Reports on the sensitivity of weeds to different species of *Azolla* are, however, generally lacking. Information regarding the effect of growth of BGA on weeds is also very scant. Since they also form a good mat when growing profusely over rice field floodwater, BGA may also be effective in this regard. Additionally, BGA are known to produce a large variety of secondary metabolites, particularly antibiotics and biotoxins (Frankmölle et al. 1992; Kulik 1995) which may act as growth deterrents to many unwanted organisms, particularly plant-disease-producing bacteria and fungi. Periminova (1964) observed a reduction in the incidence of smut in barley due to BGA inoculation. However, their in vivo efficacy in flooded rice fields particularly (due to a dilution effect) is questionable. The suppressive effect of BGA and *Azolla* on weeds is obviously influenced by the density or thickness of their bloom/mat. Species which form a thick or high density mat would be a better choice for this purpose. Another important aspect is that blooms or mats of BGA and *Azolla* have to be developed prior to the re-emergence of weeds after puddling the rice fields. Information on the effectiveness of different *Azolla* or algal species in suppressing different types of weeds in rice fields is also very lacking.

Growth-promoting effect

The effect of BGA inocula on the yield of crops in the presence of N fertilisers has commonly been ascribed to the production of growth-promoting substances by these organisms (Brown et al. 1956; Kopteva 1970; Tupik 1973). A large number of researchers have found better growth and germination of seeds of many crop plants after treating them with algal cultures or their extracts. The majority of them observed an enhancement in rice-seed germination, root and shoot growth, weight of rice grains and their protein content (Shukla and Gupta 1967; Venkataraman and Neelakantan 1967; Singh and Trehan 1973; Jacq and Roger 1977); while others found similar stimulatory effects on wheat (Gupta et al. 1967), tomato (Kaushik and Venkataraman 1979; Rodgers et al. 1979), radish (Rodgers et al. 1979; Vorontsova et al. 1988), peas (Gupta and Gupta 1972), banana (Ganapathi et al. 1994) etc. A few negative effects on the germination of rice seeds have also been documented (Pedurand and Reynaud 1987). Different opinions exist regarding the nature of these substances. Some have described them as hormones, i.e. gibberellin-like (Singh and Trehan 1973), cytokinin-like (Rodgers et al. 1979), auxin-like (Ahmad and Winter 1968) or abscisic acids (Marsalek et al. 1992); while others have described them either as vitamins, particularly vitamin B (Grieco and Desrochers 1978), or as amino acids (Watanabe 1951; Vorontsova et al. 1988), antibiotics and toxins (Metting and Pyne 1986). The production of these substances is, however, influenced by different stress factors (Marsalek et al. 1992), as well as the application of chemicals, particularly Co salts (Venkataraman and Neelankantan 1967). Mutants of some species produce more of these substances than indigenous types (Vorontsova et al. 1988). However, detailed quantitative and qualitative analyses of these substances produced by different BGA species and critical assessment of their influence on crop growth or seed germination are still lacking.

Other effects

BGA, as mentioned earlier, liberate large amounts of O_2 during photosynthesis, which establishes a comparatively thick aerobic layer of the soil-water interface in rice fields. Thind et al. (1990) made a quantitative estimate of the increase in the depth of aerobic layer ($>$300mV) in soil, which ranged from 3 mm in non-algal treatments to 15 mm with algal growth after 30 days of soil submergence. In addition to O_2, BGA also release carbonaceous metabolites which may have a stimulating effect on the heterotrophic soil microflora. If some aerobic and microaerophilic, heterotrophic N-fixing organisms such as *Azotobacter, Azospirillum, Pseudomonas* and others are inoculated along with BGA, they can make use of the excess O_2 as well as the easily oxidisable carbonaceous metabolites liberated by the BGA for their respiration and as a source of energy, respectively. This may compensate for the loss of any N through denitrification, discussed earlier, and also augment atmospheric N addition to the soil, and thus offset any possible unwanted effects caused by the BGA. Very little is known about the associated changes in soil microflora following inoculation with BGA, although Venkataraman (1975) indicated that the number of other micro-organisms is affected. In a pot experiment with *Tolypothrix tenuis* as the inoculant, Ibrahim et al. (1971) observed an increase in the total microbial population, especially the numbers of nitrifiers and the genera *Azotobacter* and *Clostridium*. Rao and Burns (1990b) employing a mixture containing BGA inocula observed an eightfold increase in bacterial numbers after 13 weeks of inoculation. However, the increase was only 2.8-fold after 21 weeks. Similarly, Rogers and Burns (1994) recorded 500-fold, 16-fold and 48-fold increases in bacteria, fungi and actinomycetes populations, respectively, in treatment inoculated with *Nostoc muscorum* over the non-inoculated one. None of these workers, however, compartmentalised or indicated the additional benefits gained due to such increased populations of beneficial microflora. The implications of relationships between BGA and other microbial populations in rice fields on biochemical changes in the soil environment have not been properly investigated. More basic studies need to be undertaken to make the BGA inoculation programme in rice fields a more effective, viable and sustainable one.

Conclusions

BGA and *Azolla* are important organisms in rice fields. They contribute significantly towards maintaining and improving the productivity of rice fields. Besides the addition of N, they considerably modify the physical, chemical, electro-chemical and biological properties of soils and the soil-water interface in rice fields in ways which are beneficial to the rice crop. The benefits accrued from organic C addition, improvement in soil physical properties, retardation of NH_3 volatilization loss, mobilisation of fixed phosphates, regulation of micronutrients, particularly Fe, Mn and Zn, affecting their availability, amelioration of the sodicity of problem soils, suppression of weeds and release of growth-promoting substances sometimes outweigh those due to the N added by them. However, these benefits can be achieved only if there is good growth of BGA and *Azolla* in rice fields, but this does not always happen under natural conditions. Hence, azolliculture/algalisation programmes need to be intensified in order to reap most of the benefits of these two useful groups in rice fields.

Future lines of research

1. Quantification of the above-mentioned benefits accrued from the growth of BGA and *Azolla* may be achieved through long-term field experimentation and the results critically assessed.
2. An assessment of the role of BGA in causing N loss through stimulation of nitrification-denitrification processes vis-à-vis N fixed by them may be made.
3. Feasibility studies on the use of *Azolla* as an agent for retarding NH_3 volatilisation of applied N may be undertaken. Selection of efficient strains for this may be made under field conditions.
4. The selection of suitable strains of BGA as solubilising agents for insoluble, fixed P in low-grade rock phosphate may be undertaken, and the utility of this ascertained.
5. Studies on the amelioration of problems of saline-sodic soils using engineered "elite" species of BGA as low-cost, effective biotechnology may be undertaken.
6. Basic studies on the effect of changes in the chemical and electro-chemical properties of soil and soil-water interfaces of rice fields due to the growth of BGA and *Azolla* on the beneficial, as well as harmful, microbial populations may be undertaken to judge the effectiveness, viability and sustainability of interactions between these groups of organisms

Acknowledgements B. Mandal gratefully acknowledges the financial assistance received from the Deutsche Forschungsgemeinschaft in the form of a INSA-DFG Visiting Scientist Fellowship for a short visit to the Institute of Agronomy in the Tropics, Georg-August University, Goettingen, Germany where part of the review was written.

References

Ahmad MR, Winter A (1968) Studies on the hormonal relationships of algae in pure culture. I. The effect of indole-3-acetic acid on the growth of blue-green and green algae. Planta 78:277–286

Aiyer RS, Aboobekar VO, Venkataraman GS, Goyal SK (1971a) Effect of algalization on soil properties and yield of IR8 rice variety. Phykos 10:34–39

Aiyer RS, Aboobekar VO, Subramoney N (1971b) Effect of blue-green algae in suppressing sulphide injury to rice crop in submerged soils. Madras Agric J 58:405–407

Aiyer RS, Salahudden S, Venkataraman GS (1972) Long-term algalization field trial with high yielding varieties of rice (*Oryza sativa* L.). Indian J Agric Sci 42:380–383

Anonymous (1975) Cultivation, propagation and utilisation of *Azolla*. Institute of Soils and Fertilisers, Chekiang Agriculture Academy, Chekiang

Antarikanonda P, Amarit P (1991) Influence of blue-green algae and nitrogen fertiliser on rice yield in saline soils. Kasetsart J Nat Sci 25:18–25

Apte SK, Thomas J (1986) Membrane electrogenesis and sodium transport in filamentous nitrogen-fixing cyanobacteria. Eur J Biochem 154:395–401

Apte SK, Haselkorn R (1990) Cloning of salinity stress-induced genes from salt tolerant nitrogen-fixing cyanobacterium *Anabaena torulosa*. Plant Mol Biol 15:723–733

Apte SK, Reddy BR, Thomas J (1987) Relationship between sodium influx and salt tolerance of nitrogen-fixing cyanobacteria. Appl Environ Microbiol 53:1934–1939

Arora SK (1969) The role of algae on the availability of phosphorus in paddy fields. Riso 18:135–138

Bertocchi C, Navarini L, Cesaro A, Anastasio M (1990) Polysaccharides from cyanobacteria. Carbohydr Polym 12:127–153

Bhardwaj KKR, Gupta IC (1971) Effect of algae on the reclamation of salt-affected soils. pp 57–58. In: Annual Report, Central Soil Salinity Research Institute, Karnal, India

Blumwald E, Mehlhorn RJ, Packer L (1983) Studies of osmoregulation in salt-adaptation of cyanobacteria with ESR spin-probe techniques. Proc Natl Acad Sci, USA 80:2599–2602

Bortoletti C, Del Re A, Silva S (1978) Phosphorus released by algae subjected to variations in temperature, pH and ionic concentrations. Agrochimica 22:5–6

Bose P, Nagpal US, Venkataraman GS, Goyal SK (1971) Solubilization of tricalcium phosphate by blue-green algae. Curr Sci 40:165–166

Bowmer KH, Muirhead WA (1987) Inhibition of algal photosynthesis to control pH and reduce ammonia volatilisation from rice floodwater. Fert Res 13:13–29

Braemer P (1927) La culture des *Azolla* an Tonkin. Rev Int Bot Appl Agric Trop 7:815–819

Brown F, Cuthbertson WFJ, Fogg GE (1956) Vitamin B_{12} activity of *Chlorella vulgaris* Beij and *Anabaena cylindrica* Lemm. Nature 177:188

Cameron HJ, Julian GR (1988) Utilisation of hydroxyapatite by cyanobacteria as their sole source of phosphate and calcium. Plant Soil 109:123–124

Cassman KG, Pingali PL (1994) Extrapolating trends from long-term experiments to farmers fields: the case of irrigated rice systems in Asia. In: Barnett V, Payne R, Roy Steiner (eds) Agricultural sustainability in economic, environmental and statistical considerations. Wiley, New York, pp 63–84

Chen CC, Dixon JB, Turner FT (1980) Iron coatings on rice roots: mineralogy and quantity influencing factors. Soil Sci Soc Am J 44:635–639

Conway GR, Pretty JN (1988) Fertiliser risks in the developing countries. Nature 334:207–208

Das SC, Mandal B, Mandal LN (1991) Effect of growth and subsequent decomposition of blue-green algae on the transformation of iron and manganese in submerged soils. Plant Soil 138:75–84

Das DK, Santra GH, Mandal LN (1995) Influence of blue-green algae in the availability of micronutrients in soils growing rice. J Indian Soc Soil Sci 43:145–146

De PK (1936) The problem of the nitrogen supply of rice. I. Fixation of nitrogen in the rice soil under waterlogged condition. Indian J Agric Sci 6:1237–1242

De PK (1939) The role of blue-green algae in nitrogen fixation in rice fields. Proc R Soc London Ser B 127:121–139

De PK, Sulaiman M (1950) Fixation of nitrogen in rice soils by algae as influenced by crop, CO_2 and inorganic substances. Soil Sci 70:137–151

De PK, Mandal LN (1956) Fixation of nitrogen by algae in rice soils. Soil Sci 81:453–458

De Datta SK (1981) Principles and practices of rice production. Wiley, New York, pp 618

Diara HF, Van Brandt H, Diop AM, Van Hove C (1987) *Azolla* and its use in rice culture in West Africa. In: *Azolla* utilisation. IRRI, Manila, pp 147–152

Dorich RA, Nelson DW, Sommers LE (1985) Estimating algal-available phosphorus in suspended sediments by chemical extraction. J Environ Qual 14:400–405

Dutta D, Mandal B, Mandal LN (1989) Decrease in availability of zinc and copper in acidic to near neutral soils on submergence. Soil Sci 147:187–195

El-Essawy AA, El-Ayouty EY, El-Ayouty YM (1985) Production of amino acids by the N_2-fixing blue-green alga *Anabaena variabilis* var. Kashiensis. Zentralbl Mikrobiol 140:333–339

Fernandes TA, Iyer V, Apte SK (1993) Differential responses of nitrogen-fixing cyanobacteria to salinity and osmotic stresses. Appl Environ Microbiol 59:899–904

Fillery IRP, Vlek PLG (1986) Reappraisal of the significance of NH_3 volatilisation as a N-loss mechanism in flooded rice fields. Fert Res 9:79–98

Fillery IRP, Roger PA, De Dutta SK (1985) Effect of N source and a urease inhibitor on NH_3 loss from flooded rice fields. II. Floodwater properties and submerged photosynthetic biomass. Soil Sci Soc Am J 50:86–91

Focht DD (1979) Microbial kinetics of nitrogen losses in flooded soils. In: Nitrogen and rice. IRRI, Manila, pp 119–134

Fogg GE, Stewart WDP, Fay P, Walsby AE (1973) The blue-green algae. Academic Press, London, pp 459

Frankmölle WP, Larsen LK, Caplan FR, Patterson GML, Knübel G, Levine IA, Moore RE (1992) Antifungal cyclic peptides from the terrestrial blue-green alga *Anabaena laxa*. I. Isolation and biological properties. J Antibiotics 45:1451–1457

Fuller WH, Roger RN (1952) Utilisation of the phosphorus of algal cells as measured by the Neubauer technique. Soil Sci 74:417–429

Ganapathi TR, Suprasanna P, Bapat VA, Rao PS (1994) Stimulatory effect of cyanobacterial extract on banana shoot tip cultures. Trop Agric (Trinidad) 71:299–302

Garcia JL, Tiedje JM (1982) Denitrification in rice soils. In: Dommergues YR, Diem HS (eds) Microbiology of tropical soils and plant productivity. Nijhoff, Junk, The Hague, pp 189–208

Gollerbach MM, Novichkova LA, Sdubrikova NV (1956) The algae of takyrs. In: Takyrs of western Turkmenia and routes of their agricultural conquest. Nauk, Moscow, pp 22–29

Grieco E, Desrochers R (1978) Production de vitamine B_{12} par une algue bleue. Can J Microbiol 24:1562–1566

Gunnison D, Alexander M (1975) Resistance and susceptibility of algae to decomposition by natural microbial communities. Limnol Oceanogr 20:64–70

Gupta AB, Gupta KK (1972) Effect of *Phormidium* extract on growth and yield of *Vigna catjang* (cowpea) T 5269. Hydrobiologia 40:127–132

Gupta AB, Agarwal V, Kushwaha AS (1967) The effect of algal growth-promoting substances on wheat. Proc Natl Acad Sci India 37B:349–355

Harrison WH, Aiyer PAS (1913) The gases of swamp rice soils: their composition and their relation to the crop. Mem Dept Agric India Chem Ser 3:65–106

Haynes RJ, Swift RS, Stephen RC (1991) Influence of mixed cropping rotations (pasturearable) on organic matter content, water-stable aggregation and clod porosity in a group of soils. Soil Till Res 19:77–87

Hirimburegama WK, Eskew DL, Zapata F, Danso SKA (1995) Recycling of phosphorus in a rice-*Azolla* cultivation system. In: Nuclear methods in soil-plant aspects of sustainable agriculture. IAEA, Vienna, pp 163–167

Ibrahim AN, Kamel M, El-Sherbeny M (1971) Effect of inoculation with alga *Tolypothrix tenuis* on the yield of rice and soil nitrogen balance. Agrokem Talajtan 20:389–400

IRRI (1987) *Azolla* utilisation. IRRI, Manila, pp 296

Jacq V, Roger PA (1977) Decrease of losses due to sulphate-reducing processes in the spermosphere of rice by pre-soaking seeds in a culture of blue-green algae. Cah ORSTOM Ser Biol 12:101–108

Jain BL, Kaushik BD (1989) Effect of algalization on crop response under saline irrigation. J Indian Soc Soil Sci 37:382–384

Janiya JD, Moody K (1981) Weed suppression in transplanted rice with *Azolla pinnata* R. Int Pest Contr 5:136–137

Janiya JD, Moody K (1984) Use of *Azolla* to suppress weeds in transplanted rice. Trop Pest Manage 30:1–6

Jha MN, Venkataraman GS, Kaushik BD (1987) Response of *Westiellopsis prolofica* and *Anabaena* sp. to salt stress. Mircen J Appl Microbiol Biotechnol 3:307–317

Johal CS (1986) Studies on the utilisation of *Azolla-Anabaena* symbiosis by flooded rice. PhD thesis. Institute of Agronomy in the Tropics, Georg-August University, Goettingen

John CD, Lemipinuntana V, Greenway H (1974) Adaptation of rice to anaerobiosis. Aust J Plant Physiol 1:513–520

Kannaiyan S, Thangaraju M, Oblisami G (1983) Effect of *Azolla* inoculation on weed growth in wetland rice. Int Rice Res Newslett 8:21

Kaushik BD (1989) Reclamative potential of cyanobacteria in salt-affected soils. Phykos 28:101–109

Kaushik BD (1994) Algalization of rice in salt-affected soils. Ann Agril Res 15:105–106

Kaushik BD, Venkataraman GS (1979) Effect of algal inoculation on the yield and vitamin C content of two varieties of tomato. Plant Soil 52:135–137

Kaushik BD, Krishna Murti GSR (1981) Effect of blue-green algae and gypsum application on physico-chemical properties of alkali soils. Phykos 20:91–94

Kaushik BD, Subhashini D (1985) Amelioration of salt-affected soils with blue-green algae. II. Improvement in soil properties. Proc Indian Natl Sci Acad Part B 51:386–389

Kaushik BD, Krishna Murti GSR, Venkataraman GS (1981) Influence of blue-green algae on saline alkali soils. Sci Cult 47:169–178

Kerby NW, Rowell P, Stewart WDP (1989) The transport, assimilation and production of nitrogenous compounds by cyanobacteria and microalgae. In: Cresswell RC, Rees TAV, Shah N (eds) Algal and cyanobacterial biotechnology. Longman, London, pp 51–90

Komatsu Y, Takagi M, Yamaguchi M (1978) Participation of iron in denitrification in waterlogged soil. Soil Biol Biochem 10:21–26

Kopteva ZHP (1970) Biosynthesis of thiamine, riboflavin and vitamin B_{12} by some blue-green algae. Mikrobiol Zh (Kiev) 32:429–433

Kröck T, Alkämper J, Watanabe I (1988a) Effect of an *Azolla* cover on the conditions in floodwater. J Agron Crop Sci 161:185–189

Kröck T, Alkämper J, Watanabe I (1988b) Temperature regime of *Azolla* under rice. J Agron Crop Sci 161:316–321

Kröck T, Alkämper J, Watanabe I (1988c) Der beitrag von *Azolla* zur unkrautbekämpfung im reisanbau. Z Pflanzenkrankr Pflanzenpathol PflanzenSchutz Sonder 11:349–355

Kulik MM (1995) The potential for using cyanobacteria (blue-green algae) and algae in the biological control of plant pathogenic bacteria and fungi. Eur J Plant Pathol 101:585–599

Kumarasinghe KS, Eskew DL (1993) Isotopic studies of *Azolla* and nitrogen fertilisation of rice. Kluwer, Dordrecht, pp 145

Kumarasinghe KS, Eskew DL (1995) *Azolla* as a nitrogen fertiliser in sustainable rice production. In: Nuclear methods in soil-plant aspects of sustainable agriculture. IAEA, Vienna, pp 147–154

Lakshmanan A, Raj SA, Kareem A (1994) Biofertilizers enhance dissolved oxygen content in water. Crop Res 8:283–286

Lales JS, Marte RS (1986) Long-term utilisation of *Azolla* as organic fertiliser for lowland rice. Phil Agric 69:459–464

Lama L, Nicolaus B, Calandrelli V, Manca MC, Romano I, Gambacorta A (1996) Effect of growth conditions on endo- and exopolymer biosynthesis in *Anabaena cylindrica* 10C. Phytochemistry 42:655–659

Lean DRS, Nalewajko C (1976) Phosphate exchange and organic phosphorus excretion by freshwater algae. J Fish Res Bd Can 33:1312–1323

Levy N, Magdassi S, Baror Y (1992) Physico-chemical aspects in flocculation of bentonite suspensions by a cyanobacterial bioflocculant. Water Res 26:249–254

Liu CC (1979) Use of *Azolla* in rice production in China. In: Nitrogen and rice. IRRI, Manila, pp 375–394

Lumpkin TA, Plucknett DL (1982) *Azolla* as a green manure: use and management in crop production. Westview tropical agriculture series no. 5. Westview, Boulder, Colo. pp 230

Mahasneh IA, Tiwari DN (1992) The use of biofertilizer of *Calothrix* sp. M103, enhanced by addition of Fe and siderophore production. J Appl Bacteriol 73:286–289

Mandal LN (1961) Transformation of iron and manganese in waterlogged rice soils. Soil Sci 91:121–126

Mandal B, Das SC, Mandal LN (1992a) Effect of growth and subsequent decomposition of blue-green algae in the transformation of phosphorus in submerged soils. Plant Soil 143:289–297

Mandal B, Das SC, Mandal LN (1992b) Effect of growth and subsequent in situ decomposition of blue-green algae on change in different forms of zinc in submerged rice (*Oryza sativa* L.) soils. Indian J Agric Sci 62:672–677

Mandal B, Chatterjee J, Hazra GC, Mandal LN (1992c) Effect of preflooding on transformation of applied zinc and its uptake by rice in lateritic soils. Soil Sci 153:250–257

Mandal B, Bhattacharya K, Mete PK, Mandal LN (1997) Effect of *Sesbania rostrata* and *Azolla microphylla* incorporation on transformation of applied zinc and copper in lateritic rice soils at different flooding periods. Biol Fertil Soils 24:394–398

Marathe KV (1972) Role of some blue-green algae in soil aggregation. In: Desikachary TV (ed) The taxonomy and biology of blue-green algae. University of Madras Press, Madras, pp 328–331

Marsalek B, Zahradnickova H, Hronkova M (1992) Extracellular abscisic acid produced by cyanobacteria under salt stress. J Plant Physiol 139:506–508

Martens DA, Frankenberger WT Jr (1992) Decomposition of bacterial polymers in soil and their influence on soil structure. Biol Fertil Soils 13:65–73

Mehta VB, Vaidya BS (1978) Cellular and extracellular polysaccharides of the blue-green alga *Nostoc*. J Exp Bot 29:1423–1430

Metting B, Pyne JW (1986) Biologically-active compounds from microalgae. Enzyme Microbial Technol 8:386–394

Moore BF, Tischer RG (1964) Extracellular polysaccharides of algae: effect of life-support systems. Science 145:586–588

Nagarajah S, Neue HU, Alberto MCR (1989) Effect of *Sesbania*, *Azolla* and rice straw incorporation on the kinetics of NH_4^+, K, Fe, Mn, Zn and P in some flooded rice soils. Plant Soil 116:37–48

Nazeer M, Prasad NN (1984) Effect of *Azolla* application on rice yield and soil properties. Phykos 23:269–272

Nekrasova KA, Aleksandrova IV (1982) Participation of Collembola and earthworms in the transformation of algal organic matter. Sov Soil Sci 14:31–39

Ngo GD (1973) The effect of *Azolla pinnata* R. Br. on rice growth. In: Biotrop Report – Second Indonesian Weed Science Conference, 2–5 April, Jogjakarta, Indonesia

Oikarinen M (1996) Biological soil amelioration as the basis of sustainable agriculture and forestry. Biol Fertil Soils 22:342–344

Osmanova RA (1979) Algal biomass in the soils of the Meshed-Messerian plains of south-western Turkmenia. Pochvovdeniye 8:109–115

Pal AK (1983) Studies on acid soils of West Bengal with special reference to micronutrients. PhD thesis. Bidhan Chandra Krishi Viswavidyalaya, West Bengal, India

Pedurand P, Reynaud PA (1987) Do cyanobacteria enhance germination and growth of rice? Plant Soil 101:235–240

Periminova GN (1964) Ecology and physiology of blue-green algae. Academy Science, Moscow

Peters GA, Toia RE Jr, Lough SM (1977) The *Azolla-Anabaena azollae* relationship. V. $^{15}N_2$ fixation, acetylene reduction and H_2 production. Plant Physiol 59:1021–1025

Ponnamperuma FN (1972) The chemistry of submerged soils. Adv Agron 24:29–96

Prasad S (1949) Nitrogen recuperation by blue-green algae in soils of Bihar and their growth on different types. J Proc Inst Chem India 21:135–140

Rains DW, Talley SN (1979) Use of *Azolla* in north America. In: Nitrogen and rice. IRRI, Manila, pp 419–433

Rao DLN, Burns RG (1990a) Use of blue-green algae and bryophyte biomass as a source of nitrogen for oilseed rape. Biol Fertil Soils 10:61–64

Rao DLN, Burns RG (1990b) The effect of surface growth of blue-green algae and bryophytes on some microbiological, biochemical and physical soil properties. Biol Fertil Soils 9:239–244

Rao DLN, Burns RG (1991) The influence of blue-green algae on the biological amelioration of alkali soils. Biol Fertil Soils 11:306–312

Reddy BR, Apte SK, Thomas J (1989) Enhancement of cyanobacterial salt tolerance by combined nitrogen. Plant Physiol 89:204–210

Reed RH, Richardson DL, Warr SRC, Stewart WDP (1984) Carbohydrate accumulation and osmotic stress in cyanobacteria. J Gen Microbiol 130:1–4

Reynaud PA, Roger PA (1981) Seasonal variations of algal flora and of N_2-fixing activity in a waterlogged sandy soil. Rev Ecol Biol Sol 18:9–27

Richards RA (1995) Improving crop production on salt-affected soils: by breeding or management? Exp Agric 31:395–408

Rodgers GA, Bergman B, Henriksson E, Udris M (1979) Utilization of blue-green algae as biofertilizers. Plant Soil 52:99–107

Roger PA (1996) Biology and management of the floodwater ecosystem in rice fields. IRRI, Manila

Roger PA, Kulasooriya SA (1980) Blue-green algae and rice. IRRI, Manila, pp 112

Roger PA, Grant IF, Reddy PM, Watanabe I (1987) The photosynthetic aquatic biomass in wetland rice fields and its effect on nitrogen dynamics. In: Efficiency of nitrogen fertilizers for rice. IRRI, Manila, pp 43–68

Roger PA, Zimmerman WJ, Lumpkin TA (1993) Microbiological management of wetland rice fields. In: Metting B (ed) Soil microbial ecology: applications in agricultural and environmental management. Dekker, New York, pp 417–455

Rogers SL, Burns RG (1994) Changes in aggregate stability, nutrient status, indigenous microbial populations and seedling emergence following inoculation of soil with *Nostoc muscorum*. Biol Fertil Soils 18:209–215

Rogers SL, Cook KA, Burns RG (1991) Microalgal and cyanobacterial soil inoculants and their effect on soil aggregate stability. In: Wilson WS (ed) Advances in soil organic matter research: the impact on agriculture and the environment. Royal Society of Chemistry Cambridge, pp 175–184

Roychoudhury P, Kaushik BD (1989) Solubilization of Mussorie rock phosphates by cyanobacteria. Curr Sci 58:569–570

Roychoudhury P, Pillai GR, Pandey SL, Krishna Murti GSR, Venkataraman GS (1983) Effect of blue-green algae on aggregate stability and rice yield under different irrigation and nitrogen levels. Soil Till Res 3:61–66

Roychoudhury P, Kaushik BD, Venkataraman GS (1985) Response of *Tolypothrix ceylonica* to sodium stress. Curr Sci 54:1181–1183

Saha KC, Mandal LN (1979) Effect of algal growth on the availability of P, Fe, and Mn in rice soils. Plant Soil 52:139–149

Saha KC, Panigrahi BC, Singh PK (1982) Blue-green algae or *Azolla* additions on the nitrogen and phosphorus availability and redox potential of a flooded rice soil. Soil Biol Biochem 14:23–26

Saito M, Watanabe I (1978) Organic matter production in rice field floodwater. Soil Sci Plant Nutr 24:427–440

Sajwan KS, Lindsay WL (1986) Effect of redox on zinc deficiency in paddy rice. Soil Sci Soc Am J 50:1264–1269

Sampaio AJ, Fiore MF, Ruschel AP (1984) Utilisation of radioactive P (^{32}P) by *Azolla-Anabaena* and its transfer to rice plants. In: Silver WS, Schröder EC (eds) Practical application of

Azolla for rice production. Nijhoff, Junk, The Hague, pp 163–167

Sankaram A (1971) Work done on blue-green algae in relation to agriculture. Technical Bulletin no. 27. Indian Council of Agricultural Research, New Delhi

Satapathy KB, Singh PK (1985) Control of weeds by *Azolla* in rice. J Aquat Plant Manage 23:40–42

Schulten JA (1985) Soil aggregation by cryptogams of a sand prairie. Am J Bot 72:1657–1661

Sharma ML, Bhardwaj GS, Chauhan YS (1989) Study on the effect of biofertilizer, pyrite and gypsum on paddy in the salt-affected soils. Indian J Agron 34:129–130

Shen ZH, Leu SE, Chen KZ, Gi SA (1963) The initial experiment on *Azolla's* nitrogen fixing ability. Pedol Bull Peking 4:45–48

Shukla AC, Gupta AB (1967) Influence of algal growth-promoting substances on growth, yield and protein contents of rice plants. Nature 213:744

Singh RN (1950) Reclamation of "usar" lands in India through blue-green algae. Nature 165:325–326

Singh RN (1961) Role of blue-green algae in nitrogen economy of Indian agriculture. Indian Council of Agricultural Research, New Delhi

Singh VP, Trehan T (1973) Effect of extracellular products of *Aulosira fertilissima* on the growth of rice seedlings. Plant Soil 38:457–464

Singh AL, Singh PK (1987) Influence of *Azolla* management on the growth, yield of rice and soil fertility. II. N and P contents of plants and soil. Plant Soil 102:49–54

Singh PK, Panigrahi BC, Satapathy KB (1981) Comparative efficiency of *Azolla*, blue-green algae and other organic manures in relation to N and P availability in a flooded rice soil. Plant Soil 62:35–44

Singh DV, Tripathi AK, Kumar HD (1991) Isolation and characterisation of salinity resistant mutant of a nitrogen-fixing cyanobacterium, *Anabaena doliolum*. J Appl Bacteriol 71:207–210

Singh AK, Chakravarty D, Singh TPK, Singh HN (1996) Evidence for a role for L-proline as a salinity protectant in the cyanobacterium *Nostoc muscorum*. Plant Cell Environ 19:490–494

Sisworo WL, Eskew DL, Sisworo WH, Rasjid H, Kadarusman H, Solahuddin S, Soepardi G (1990) Studies on the availability of *Azolla* N and urea N for rice growth using ^{15}N. Plant Soil 128:209–220

Sisworo EL, Rasjid H, Sisworo WH, Wemay J, Haryanto (1995) Use of ^{15}N to determine the N-balance of *Azolla*-N and urea-N applied to wetland rice. In: Nuclear methods in soil-plant aspects of sustainable agriculture. IAEA, Vienna, pp 155–162

Sprent JI, Sprent P (1990) Nitrogen fixing organisms – pure and applied aspects. Chapman and Hall, London, pp 256

Stewart WDP, Fitzgerald GP, Burns RH (1968) Acetylene reduction by nitrogen-fixing blue-green algae. Arch Microbiol 62:336–348

Subhashini D, Kaushik BD (1981) Amelioration of sodic soils with blue-green algae. Aust J Soil Res 19:361–367

Tel-Or E, Rozen A, Ofir Y, Kobiler D, Schönfeld M (1991) Metabolic relations and intercellular signals in the *Azolla-Anabaena* association. Isr J Bot 40:171–181

Thind HS, Rowell DL, Harris PJ (1990) Effect of algae and various nitrogen fertilisers on pH and redox conditions of soil and flood water of paddy soils in relation to nitrogen transformations. Trans Int Cong Soil Sci 4:750–751

Thomas J (1977) Biological nitrogen fixation. Nucl India 15:2–8

Thompson PA, Oh HM, Rhce GY (1994) Storage of phosphorus in nitrogen-fixing *Anabaena flos-aquae* (cyanophyceae). J Phycol 30:267–273

Tisdall JM, Oades JM (1982) Organic matter and water stable aggregates in soils. J Soil Sci 33:141–163

Tiwari TN, Kumar R, Singh R, Yadav DN (1991) Response of blue-green algae fertiliser with molybdenum on soil properties and yield of rice (*Oryza sativa* L.). Indian J Agron 36:411–413

Tung HF, Shen TC (1981) Studies on the *Azolla pinnata-Anabaena Azollae* symbiosis: growth and nitrogen fixation. New Phytol 87:743–749

Tupik ND (1973) Study of the content of group B vitamins in cells of some blue-green algae in dependence on the culture age. Ukr Bot Zh 30:636–639

Van Hove C (1989) *Azolla* and its multiple uses with emphasis on Africa. FAO, Rome, pp 53

Venkataraman GS (1975) The role of blue-green algae in tropical rice cultivation. In: Stewart WDP (ed) Nitrogen fixation by free-living micro-organisms. Cambridge University Press, Cambridge, pp 207–218

Venkataraman GS (1981) Blue-green algae for rice production – a manual for its promotion. Soils Bulletin no. 46. FAO, Rome

Venkataraman GS, Neelakantan S (1967) Effect of cellular constituents of nitrogen fixing blue-green alga *Cylindrospermum* on root growth of rice plants. J Gen Appl Microbiol 13:53–62

Ventura W, Watanabe I (1993) Green manure production of *Azolla microphylla* and *Sesbania rostrata* and their long-term effects on rice yields and soil fertility. Biol Fertil Soils 15:241–248

Villegas GG (1985) Effect of *Azolla* cover on nitrogen in flooded Maahas clay. MSc thesis. University of the Philippines, Lös Banos

Vlek PLG, Craswell ET (1979) Effect of nitrogen source and management on ammonia volatilisation losses from flooded rice-soil system. Soil Sci Soc Am J 43:352–358

Vlek PLG, Craswell ET (1981) NH_3 volatilisation from flooded soils. Fert Res 2:247–259

Vlek PLG, Fugger W, Biker U (1992) The fate of fertiliser N under *Azolla* in wetland rice. In: Proceedings of the 2nd ESA Congress, Warwick University, Warwick, UK, pp 376–377

Vlek PLG, Diakite MY, Mueller H (1995) The role of *Azolla* in curbing ammonia volatilisation from flooded rice systems. Fert Res 42:165–174

Vorontsova GV, Romanova NI, Postnova TI, Selyakh IO, Gusev MV (1988) Biostimulating effect of cyanobacteria and ways to increase it. I. Use of mutants – superproducers of amino acids. Moscow Univ Biol Sci Bull 43:14–19

Wagner GM (1997) *Azolla*: a review of its biology and utilization. Bot Rev 63:1–26

Watanabe A (1951) Production in cultural solution of some amino acids by the atmospheric nitrogen fixing blue-green algae. Arch Biochem Biophys 34:50

Watanabe I (1987) Summary report of the *Azolla* programme of the International Network on Soil Fertility and Fertiliser Evaluation for Rice. In: *Azolla* utilisation. IRRI, Manila, pp 197–205

Watanabe A, Kiyohara T (1960) Decomposition of blue-green algae as affected by the action of soil bacteria. J Gen Appl Microbiol 5:175–179

Watanabe I, Roger PA (1984) Nitrogen fixation in wetland rice fields. In: Subba Rao NS (ed) Current developments in biological nitrogen fixation. Oxford, IBH, New Delhi, pp 237–276

Watanabe I, Lee KK, Alimagno BV, Sato M, Del Rosario DC, De Guzman MR (1977) Biological nitrogen fixation in paddy field studies by in situ acetylene-reduction assays. IRRI Res Pap Ser 3:1–16

Watanabe I, Bai KZ, Berja NS, Espina LR, Ho O, Subidhi RPR (1981) The *Azolla-Anabaena* complex and its use in rice culture. IRRI Res Pap Ser 69

Wolf AM, Baker DE, Pionke HB, Kunichi HM (1985) Soil test for estimating labile, soluble and algal available phosphorus in agricultural soils. J Environ Qual 14:341–348

Yanni YG (1992) The effect of cyanobacteria and *Azolla* on the performance of rice under different levels of fertiliser nitrogen. World J Microbiol Biotechnol 8:132–136