Influence of Low pH Stress on Growth, Specific Biochemical Parameters and Antioxidants amongst Selected Nostoc Strains

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Abstract

The present study focused on the influence of low pH on growth, specific biochemical parameters and antioxidants amongst Nostoc strains grown under control (pH 7.0) and low pH (pH 4.5) medium. Cell dry weight, chlorophyll content, total soluble proteins and extracellular ammonia release reduced due to low pH stress of growing media compared to control grown cultures. Nitrogenase activity was reduced in two and increased in remaining strains due to low pH. Proline content increased whereas glycerol decreased in all low pH tolerant Nostoc strains whereas glycine betaine and lipid peroxidation depicted a variable response.

Keywords
Cyanobacteria, Nostoc, Chlorophyll, Biochemical attributes, Lipid peroxidation, Proline and low pH

Introduction

Cyanobacteria are a group of cosmopolitan prokaryotes, which are found in diverse ecological niche including soil, rocks, fresh water and even in salt water (Hoffmann, 1989; Kaushik, 1994). Most of the research work undertaken has focussed on species of Nostoc, Anabaena, Tolypothrix, Aulosira, Cylindrospermum, Scytonema and Westiellopsis which are widespread in Indian rice field soils and are known to contribute significantly to the soil fertility (Venkataraman, 1981). Amongst different soil factors, soil pH is particularly important and directly affects cyanobacterial distribution as well as their abundance (Sardeshpande and Goyal, 1981). Under laboratory conditions,
these have generally been reported to prefer neutral to slightly alkaline medium for optimum growth and are normally absent at pH values below 4 or 5 (Gerloff et al., 1952; Kratz et al., 1955). A phytoplankton survey of 10 lakes in Bavarian Forest as well as the lignite mining districts of Bavaria (Upper Palatine) and Lusatia, covering a pH gradient from 8.0 to 2.8, demonstrated that acid-tolerant cyanobacteria do exist (Steinberg et al., 1998). Low pH stress is a potential abiotic stress negatively affecting the growth, survival, pigmentation, protein profiles, membrane structures and biological nitrogen fixation process in cyanobacteria. In 2006, Tandeau de Marsac and Houmard reported that, to survive in extreme or variable environments, cyanobacteria have developed specific regulatory systems in addition to more general mechanisms that are equivalent to those found in other prokaryotes or photosynthetic bacteria. There is limited information on low pH tolerance mechanism in terms of growth and biochemical attributes, however, studies have been conducted in relation to different abiotic stresses like osmotic, salinity, organic, water and UV-radiation. In view of this, the aim of the present work was to study the effect of low pH on growth, total soluble proteins, extracellular ammonia release, nitrogenase activity and antioxidants in selected Nostoc strains isolated from low pH soils of India, against fresh water isolate from IARI rice field.

Materials and Methods

Cyanobacterial strains and cultural conditions

Low pH tolerant Nostoc strains (Ns1, Ns2, Ns3, Ns4) isolated from acidic soils of India as well as fresh water strain Nostoc punctiforme (CCC No. 672, Ns5) which was an isolate from IARI rice field, were procured from the culture collection of CCUBGA, ICAR-IARI. These strains were grown and maintained in BG-11 (N deficient) medium at 28±2°C temperature under photoperiod of 16:8 hours light and dark cycle with light intensity of 52-55µmole photon m⁻²s⁻¹ in culture room. The pH of medium for Ns1 to Ns4 was maintained at 7.0 (control) and 4.5 (low pH) under two sets of experiment. Low pH was maintained with 0.1M citrate buffer (pH 3.1) comprising 0.1M Citric acid monohydrate and 0.1M Trisodium citrate dihydrate after filter sterilization. Nostoc punctiforme (Ns5) was grown and maintained at pH 7.0 only as it did not tolerate low pH medium. Known volumes of cyanobacterial suspension grown under control (pH 7.0) and low pH (pH 4.5) medium was used during exponential phase of growth (14th day) for estimation of growth, specific biochemical attributes and antioxidants.

Cell dry weight (CDW, mg ml⁻¹) was determined gravimetrically using a known volume of cyanobacterial suspension by centrifugation at 5000g for 10 min. The washed and harvested pellet was dried at 60°C temperature till constant weight was achieved (Sorokin 1945). The chlorophyll content (µg ml⁻¹) was estimated in methanolic extract with absorbance measured at 650 and 665nm (Litchtenthaler and Buschman, 2001). Total soluble proteins were measured at 650 nm spectrophotometrically following the method of Lowry et al., (1951). The chlorophyll content (µg ml⁻¹) was estimated in methanolic extract with absorbance measured at 650 and 665nm (Litchenthaler and Buschman, 2001). Total soluble proteins were measured at 650 nm spectrophotometrically following the method of Lowry et al., (1951). Phenol hypochlorite method was used to estimate extracellular ammonia (µmole NH₄⁺ ml⁻¹, Solorzano1969). Nitrogenase activity was measured as acetylene reducing activity following the method of Hardy et al., (1968). Proline content (µg ml⁻¹) in cyanobacterial homogenate was determined spectrophotometrically according to the method of Bates et al., (1973). Modified procedures developed by Lambert and Neish (1950) and that of Grieve and Grattan (1983) were used to study glycerol (µg ml⁻¹) and glycine betaine content.
Concentration of malondialdehyde was measured for lipid peroxidation potential (µg ml\(^{-1}\), Heath & Packer 1968).

For statistical analyses, the triplicate set of data for the various parameters evaluated were subjected to ANOVA (analysis of variance) and the software Statistical Package for Social Sciences (SPSS Version 16.0) was used for calculating SE, SD and CD.

**Results and Discussion**

Comparative cell dry weight (mg ml\(^{-1}\)) as well as chlorophyll content decreased in Ns1, Ns2, Ns3 and Ns4 under low pH growing conditions as compared to control, however, fresh water strain, Ns5 did not tolerate low pH stress and no growth was observed. The percent decrease in the cell dry weight varied from a lowest of 12% in Ns3 to the highest of 25% by Ns1 and the treatment effect was observed to be significant in all. On the other hand, percent decrease in chlorophyll content ranged from a lowest of 17% in Ns3 to the highest of 45% in Ns1 (Table 2). Cell dry weight under control grown conditions showed a highest of 1.90 mg ml\(^{-1}\) in Ns1 to the lowest of 1.19 mg ml\(^{-1}\) in Ns3. The other two strains showed cell dry weight of 1.77 mg ml\(^{-1}\) (Ns2) and 1.166 mg ml\(^{-1}\) (Ns4) respectively. However, under low pH grown cultures, the range in cell dry weight was from a highest of 1.51 mg ml\(^{-1}\) to the lowest of 1.05 mg ml\(^{-1}\) in Ns2 and Ns3 while strains Ns1 and Ns2 depicted the cell dry weight of 1.43 mg ml\(^{-1}\) and 1.51 mg ml\(^{-1}\) respectively. The fresh water strain showed cell dry weight of 1.32 mg ml\(^{-1}\) under normal pH of 7.0 (Table 1). **Table 1**. Total soluble proteins also decreased due to low pH stress in *Nostoc* strains (Ns1, Ns2, Ns3 and Ns4) as compared to normal pH growing conditions. The fresh water isolate, Ns5 showed the total soluble proteins of 0.71 mg ml\(^{-1}\) under control grown conditions. Percent reduction in total soluble proteins was observed to be in the range of 14% to 24% by Ns4 and Ns2 due to low pH stress (Table 2). The total soluble proteins were highest between 7.4 and 8.0 is optimum (Rippka *et al.*, 1979; Bano and Siddiqui, 2004).
(0.93 mg ml⁻¹) in Ns1 and lowest (0.69 mg ml⁻¹) in Ns4 while Ns2 and Ns3 depicted a total soluble proteins content 0.78 mg ml⁻¹ and 0.80 mg ml⁻¹ at pH 7.0. At pH 4.5, Ns1 showed highest (0.73 mg ml⁻¹) followed by 0.69 mg ml⁻¹ (Ns3), 0.59 mg ml⁻¹ (Ns4) and Ns2 showed lowest (0.59 mg ml⁻¹) total soluble proteins (Table 1). Extracellular ammonia release is a very important attribute of heterocystous cyanobacteria and ranged from a highest of 275.20 µmole NH₄⁺ ml⁻¹ (Ns1) to lowest of 68.90 µmole NH₄⁺ ml⁻¹ (Ns4), while the other two strains Ns2 and Ns3 depicted 191.10 µmole NH₄⁺ ml⁻¹ and 87.70 µmole NH₄⁺ ml⁻¹ under control grown conditions. When these cultures were grown under low pH medium, the extracellular ammonia release ranged from 165.10 µmole NH₄⁺ ml⁻¹ in Ns1 to 30.70 µmole NH₄⁺ ml⁻¹ in Ns4 while, the Strains Ns2 and Ns3 depicted the extracellular ammonia release of 75.10 µmole NH₄⁺ ml⁻¹ and 38.80 µmole NH₄⁺ ml⁻¹ respectively. Fresh water isolate showed an extracellular ammonia release of 103.40 µmole NH₄⁺ ml⁻¹ and percent decrease in extracellular ammonia release varied as a highest of 61% to the lowest of 40% in Ns2 and Ns1 due to low pH stress in the growing medium (Table 2). The reduction in extracellular ammonia release could be due to enhanced glutamine synthetase activity or reduced nitrogenase activity under low pH stress condition.

Fresh water strain does not tolerate low pH stress growing condition as cyanobacteria have been reported to prefer alkaline condition for their growth which suggests that there is probably an acid barrier which these organisms are not able to overcome, hence, this group of algae is excluded from low pH environment. However, in other strains of Nostoc (Ns1, Ns2, Ns3, Ns4) there was a significant decrease observed in cell dry weight, chlorophyll content, total soluble proteins and extracellular ammonia release due to low pH stress which could be as a result of lack of control over internal pH resulting in growth limitation (Padan et al., 1981; Booth 1985; Padan and Schuldiner 1987). At low pH, cells spend energy for maintenance of internal pH necessary for important cell functions (Raven and Lucas 1985). Low pH tolerance shown by cyanobacteria suggests that these organisms can adapt to variable pH conditions (Burja et al., 2002). However, the growth rate of diatoms was not affected by pH range of 7.4 to 8.2 and it was significantly lower at pH of 6.8. Highest nitrogenase activity of 1.96 nmole C₂H₄ ml⁻¹h⁻¹ was exhibited by Ns2 followed by 0.30 nmole C₂H₄ ml⁻¹h⁻¹ in Ns1, 0.32 nmole C₂H₄ ml⁻¹h⁻¹ in Ns3 and the lowest of 0.28 nmole C₂H₄ ml⁻¹h⁻¹ was shown in Ns4 under control grown culture conditions. When the cultures were grown under low pH stress medium, nitrogenase activity dropped to a highest of 0.83 nmole C₂H₄ ml⁻¹h⁻¹ in Ns3 and lowest of 0.27 nmole C₂H₄ ml⁻¹h⁻¹ in Ns1. The other two strains, Ns2 and Ns4 showed the nitrogenase activity of 0.64 nmole C₂H₄ ml⁻¹h⁻¹ and 0.64 nmole C₂H₄ ml⁻¹h⁻¹ respectively (Table 1). Low pH stress condition reduced the nitrogenase activity by 10% and 67% in Nostoc strains Ns1 and Ns2, however, it increased in Ns3 and Ns4 by 159% and 139% and fresh water isolate showed nitrogenase activity of 1.73 nmole C₂H₄ ml⁻¹h⁻¹ (Table 2). There was a strain variability recorded in terms of expression of nitrogenase activity due to low pH condition. Comparative evaluation of selected parameters amongst Nostoc strains grown under control (pH 7.0) and low pH (pH 4.5) conditions depicted that Nostoc strain Ns1, an isolate from Alipurduar (West Bengal), India showed maximum cell dry weight, chlorophyll content, total soluble proteins and extracellular ammonia release while Ns4 (an isolate from Mokokchung, Nagaland soil) showed lowest chlorophyll, total soluble proteins and extracellular ammonia release under control (pH 7.0)
grown conditions. The cell dry weight was lowest in Ns3, which was an isolate from Ernakulam Kerala soil. When these cultures were grown under low pH medium, Ns1 again depicted highest total soluble proteins and extracellular ammonia release, whereas, Ns2 showed highest cell dry weight and Ns3 exhibited maximum chlorophyll content. On the other hand Ns2 showed lowest chlorophyll content and total soluble proteins, whereas, cell dry weight was lowest in Ns3 and extracellular ammonia release was lowest in Ns4.

Results calculated for non-enzymatic antioxidants namely proline, glycerol, glycine betaine and lipid peroxidation indicated a variable behaviour by Nostoc strains grown under control and low pH conditions. The low pH stress enhanced selected antioxidants like proline, lipid peroxidation and glycine betaine, however, a reverse trend was shown in terms of glycerol accumulation. Proline content increased in Nostoc strains under pH 4.5 as compared to control grown cultures. Under low pH stress, the highest proline content of 132.80 µg ml⁻¹ was recorded in Ns1 and the lowest of 76.68 µg ml⁻¹ was shown by Ns3. The other two strains showed proline content of 102.63 µg ml⁻¹ (Ns2) and 101.47 µg ml⁻¹ (Ns4) respectively. When Nostoc strains were grown at control pH medium, the proline content of 86.38 µg ml⁻¹ was highest in Ns2 followed by a proline content of 75.54 µg ml⁻¹ (Ns1), 64.76 µg ml⁻¹ (Ns4) with the lowest of 61.70 µg ml⁻¹ (Ns3). Fresh water isolate showed a proline content of 64.34 µg ml⁻¹ which was similar to the proline content depicted by Ns4 (Table 3).

**Table 1** Comparative Cell Dry Weight (CDW, mg ml⁻¹), chlorophyll (µg ml⁻¹), total soluble proteins (TSP, mgml⁻¹), extracellular ammonia release (EAR, µmole ml⁻¹) and nitrogenase activity (nmoles C₂H₄ ml⁻¹ h⁻¹) amongst selected Nostoc strains grown under control (pH-7.0) and low pH (pH-4.5) conditions (Mean ± SD; n=3)

| Strains*/Treatments | CDW     | Chlorophyll | TSP     | EAR      | Nitrogenase|
|---------------------|---------|-------------|---------|----------|------------|
| Ns1 C1              | 1.90 ± 0.076ᵃ | 18.70 ± 1.108ᵇ | 0.93 ± 0.055ᵃ | 275.20 ± 3.995ᵃ | 0.30 ± 0.003ᵉ |
| T1                  | 1.43 ± 0.053ᵈ | 10.22 ± 2.656ᵈ | 0.73 ± 0.013ᵇ | 165.10 ± 1.212ᶜ | 0.27 ± 0.006ᵉ |
| Ns2 C2              | 1.77 ± 0.020ᵇ | 13.00 ± 0.847ᶜ | 0.78 ± 0.029ᵇ | 191.10 ± 2.163ᵇ | 1.96 ± 0.055ᵃ |
| T2                  | 1.51 ± 0.102ᵈ | 7.58 ± 1.589ᵉ | 0.59 ± 0.033ᵈ | 75.10 ± 1.539ᶠ | 0.64 ± 0.001ᵈ |
| Ns3 C3              | 1.19 ± 0.068ᵍ | 15.55 ± 0.674ᵇ | 0.80 ± 0.016ᵇ | 87.70 ± 1.652ᵉ | 0.32 ± 0.013ᵉ |
| T3                  | 1.05 ± 0.080ʰ | 12.91 ± 0.201ᶜ | 0.69 ± 0.026ᵉ | 38.80 ± 0.458ʰ | 0.83 ± 0.003ᵉ |
| Ns4 C4              | 1.66 ± 0.054ᶜ | 12.66 ± 0.117ᶜ | 0.69 ± 0.064ᶜ | 68.90 ± 2.272ᵍ | 0.28 ± 0.011ᵉ |
| T4                  | 1.39 ± 0.017ᵉ | 9.01 ± 0.063ᵈ | 0.59 ± 0.027ᵈ | 30.70 ± 1.353ʰ | 0.67 ± 0.010ᵈ |
| Ns5 C5              | 1.32 ± 0.024ᶠ | 16.76 ± 0.734ᵃᵇ | 0.71 ± 0.026ᶜ | 103.40 ± 2.551ᵈ | 1.73 ± 0.041ᵇ |
| T5                  | ND     | ND          | ND      | ND       | ND         |
| SEm (±)             | 0.037   | 0.617       | 0.021   | 1.285    | 0.015      |
| CD (0.05%)          | 0.112   | 1.850       | 0.063   | 3.854    | 0.044      |

* Nostoc strains (Ns1, Ns2, Ns3, Ns4, Ns5)
† Treatments: Control (C1, C2, C3, C4, C5); low pH (T1, T2, T3, T4, T5)
≠ Acetylene reducing activity
Different superscripts in the same column represent significant differences between samples (p< 0.05)
ᵉ ND- Not detected
Table.2 Percent change in cell dry weight (CDW), chlorophyll, total soluble proteins (TSP), extracellular ammonia release (EAR) and nitrogenase activity amongst selected *Nostoc* strains under low pH stress condition as compared to control

| Strains | CDW  | Chlorophyll | TSP  | EAR  | Nitrogenase |
|---------|------|-------------|------|------|-------------|
| Ns1     | 25%  | 45%         | 22%  | 40%  | 10%         |
| Ns2     | 15%  | 42%         | 24%  | 61%  | 67%         |
| Ns3     | 12%  | 17%         | 14%  | 56%  | 159%        |
| Ns4     | 16%  | 29%         | 14%  | 55%  | 139%        |

*Arrows denotes percent increase (↑) and decrease (↓) in specific parameter

Table.3 Comparative proline (µg mg⁻¹), glycerol (µg mg⁻¹), glycine betaine (µg mg⁻¹) and lipid peroxidation (µg mg⁻¹) amongst selected *Nostoc* strains grown under control (pH-7.0) and low pH (pH-4.5) condition (Mean ± SD; n=3)

| Strains*/* Treatments† | Proline   | Glycerol   | Glycine betaine | Lipid peroxidation |
|------------------------|-----------|------------|-----------------|-------------------|
| Ns1 C1                 | 75.94 ± 1.279a | 34.10 ± 1.463d | 200.76 ± 2.001a | 4.19 ± 0.047b     |
| T1                     | 132.80 ± 2.558a | 28.79 ± 0.770c | 109.22 ± 1.044g | 3.48 ± 0.068c     |
| Ns2 C2                 | 86.38 ± 0.483c | 46.60 ± 1.016b | 145.55 ± 0.688f | 3.24 ± 0.094d     |
| T2                     | 102.63 ± 1.675b | 25.74 ± 0.438f | 162.18 ± 0.168e | 5.96 ± 0.060a     |
| Ns3 C3                 | 61.70 ± 0.796d | 34.28 ± 0.194d | 151.18 ± 1.529e | 2.18 ± 0.013g     |
| T3                     | 76.68 ± 0.633d | 14.83 ± 0.848a | 200.73 ± 2.988a | 2.85 ± 0.073e     |
| Ns4 C4                 | 64.76 ± 0.659c | 42.19 ± 0.308e | 185.35 ± 0.175b | 2.51 ± 0.013f     |
| T4                     | 101.47 ± 3.186b | 21.09 ± 1.272e | 155.41 ± 1.379d | 2.85 ± 0.026e     |
| Ns5 C5                 | 64.34 ± 1.096ef | 48.76 ± 0.321a | 162.04 ± 0.679c | 3.50 ± 0.045c     |
| T5                     | ND#        | ND         | ND              | ND                |
| SEm (±)                | 0.996      | 0.501      | 0.789           | 0.032             |
| CD (0.05%)             | 2.987      | 1.501      | 2.366           | 0.097             |

* Nostoc strains (Ns1, Ns2, Ns3, Ns4, Ns5)
† Treatments: control (C1, C2, C3, C4, C5); low pH (T1, T2, T3, T4, T5)
Different superscripts in the same column represent significant differences between samples (p<0.05)
# ND- Not detected

Table.4 Percent change in proline, glycerol, glycine betaine and lipid peroxidation amongst selected *Nostoc* strains under low pH stress condition as compared to control

| Strains | Proline | Glycerol | Glycine betaine | Lipid peroxidation |
|---------|---------|----------|-----------------|-------------------|
| Ns1     | 75%↑    | 16%↓     | 46%↓            | 17%               |
| Ns2     | 19%↑    | 45%↓     | 11%↑            | 84%↑              |
| Ns3     | 24%↑    | 57%↓     | 33%↑            | 31%↑              |
| Ns4     | 57%↑    | 50%↓     | 16%↑            | 14%↑              |

*Arrows denotes percent increase (↑) and decrease (↓) in specific parameter
Glycerol content also decreased due to low pH stress compared to control and the percent decrease varied from 16% in Ns1 to 57% in Ns3 (Table 4). Fresh water isolate (Ns5) showed a highest glycerol content of 48.76 µg ml\(^{-1}\), followed by glycerol content of 46.60 µg ml\(^{-1}\) (Ns2), 42.19 µg ml\(^{-1}\) (Ns4), 34.28 µg ml\(^{-1}\) (Ns3) with the lowest of 34.10 µg ml\(^{-1}\) (Ns1) under control grown conditions. However at low pH, the glycerol content was highest (28.79 µg ml\(^{-1}\)) in Ns1 and lowest (14.83 µg ml\(^{-1}\)) in Ns3, while the other two strains, Ns2 and Ns4 depicted the glycerol content of 25.74 µg ml\(^{-1}\) and 21.09 µg ml\(^{-1}\) respectively (Table 3). Glycine betaine was highest (200.76 µg ml\(^{-1}\)) in Ns1 followed by 151.18 µg ml\(^{-1}\) in Ns3, 185.35 µg ml\(^{-1}\) in Ns4 and Ns2 showed a lowest glycerol content of 145.55 µg ml\(^{-1}\) at pH 7.0 whereas, fresh water isolate depicted a glycine betaine level of 162.04 µg ml\(^{-1}\) which was at par with the glycine betaine content of 162.18 µg ml\(^{-1}\) under low pH stress by Ns2. Under pH stress, the glycine betaine was highest (200.73 µg ml\(^{-1}\)) in Ns3 whereas Ns1 showed lowest (109.22 µg ml\(^{-1}\)) glycine betaine content while, the other two strains, Ns2 and Ns4 showed 162.18 µg ml\(^{-1}\) and 155.41 µg ml\(^{-1}\) of glycine betaine content respectively (Table 3). Nostoc strains exhibited a variable behaviour in terms of glycine betaine which increased by 11% and 33% in Ns2 and Ns3 due to low pH stress, whereas a decrease of 16% and 46% was recorded by Ns4 and Ns1 (Table 4). Lipid peroxidation also depicted a variability in terms of response towards low pH stress vis-à-vis control grown cultures with the highest of 4.19 µg ml\(^{-1}\) recorded by Ns1 and lowest of 2.18 µg ml\(^{-1}\) recorded by Ns3 under pH 7.0. The fresh water isolate showed lipid peroxidation of 3.50 µg ml\(^{-1}\). At low pH, Ns2 showed highest (5.96 µg ml\(^{-1}\)) lipid peroxidation followed by Ns1 (3.48 µg ml\(^{-1}\)), Ns3 (2.85 µg ml\(^{-1}\)) and Ns4 (2.83 µg ml\(^{-1}\)) (Table 3). Lipid peroxidation was more or less similar in Ns3 and Ns4 when the cultures were grown under control (pH 7.0) and/or low pH stress condition. Lipid peroxidation decreased by 17% in Ns1 and increased by 84%, 31% and 14% in Ns2, Ns3 and Ns4 due to low pH stress as compared to control (Table 4). High degree of lipid peroxidation has been reported in Synechococcus and Nostoc muscorum (Rehman et al., 2011). Stress induced enhancement in these parameters is supported by the reports of Zeesan and Prasad (2009) and Sunderam et al., (2011). The stress and the resistance is governed through modulation of antioxidant enzymes as well as compounds like proline, glycine betaine, glutathione and ascorbate and their increased malondialdehyde levels. Increased level of these antioxidants under stress condition is indicative of a correlation between free radical generation and proline accumulation (Zeesan and Prasad 2009). This is in agreement with other reports on Spirulina platensis and Westeillopsis prolifica (Choudhary et al.2007). The cyanobacteria can counteract the toxic effect of abiotic stress induced free radicals by increasing antioxidants defense mechanisms.

Under control conditions of growth, proline content was highest in Ns 2, whereas glycerol was maximum in Ns5 and Ns1 showed maximum glycine betaine and lipid peroxidation. However, the proline and lipid peroxidation was lowest in Ns3, while glycerol and glycine betaine were lowest in Ns1 and Ns2. Highest proline content and glyceral was depicted by Ns1 whereas glycine betaine and lipid peroxidation were maximum in Ns3 and Ns2 when cultures were grown under low pH stress. With pH stress proline and lipid peroxidation were lowest in Ns4 whereas, glycerol was lowest in Ns3 and glycine betaine was lowest in Ns1.

In conclusions, comparative studies undertaken amongst Nostoc strains indicated
that low pH condition in the growing medium reduced growth in terms of cell dry weight, chlorophyll content, extracellular ammonia release and total soluble proteins. The influence of low pH on nitrogenise activity was variable. Low pH stress increased proline content and increased glycerol, however, its influence on other parameters like glycine betaine and lipid peroxidation was variable. The study clearly indicated the differential behaviour of Nostoc strains in terms of selected parameters due to low pH stress situations and such strains can be further used to understand the in-depth mechanisms underlying low pH tolerance amongst cyanobacteria.

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