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Anabaena variabilis as a Promising Biofertiliser and Biochemical Enhancer of Two Local Bread Wheat Cultivars

Rana Nassour [1] and Seraoos Mohamad [2]

[1] Department of Plant Biology, Faculty of Science, Tishreen University, Latakia, Syria
[2] Department of Plant Biology, Faculty of Science, Damascus University, Damascus, Syria

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ABSTRACT

The potential of *Anabaena variabilis* as a biofertiliser for two *Triticum aestivum* L. cultivars –Doma 6 (D6) and Bohoth 8 (B8) was tested. Three treatments were used: T1 (control, irrigated with BG11), T2 (control – N, irrigated with BG11 without $NaNO_3$), and T3 (inoculated with *A. variabilis* and irrigated with BG11 without $NaNO_3$) to evaluate their impact on pigment, carbohydrate and protein contents. Measurements were taken at 14, 21, 28 and 35 days of seedling growth (three replicates each). The results indicated that nitrogen deficiency (T2) led to a general decrease in all the studied parameters. In contrast, the presence of *A. variabilis* (T3) enhanced chlorophyll a, chlorophyll b, carotenoid, carbohydrate and protein contents in both studied cultivars, with significantly greater effects observed in the D6 cultivar.

KEYWORDS

Carbohydrate, carotenoids, chlorophyll, cyanobacteria, protein, *Triticum aestivum*

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1. Introduction

Wheat is the most widely cultivated cereal crop worldwide, with approximately 220.4 million hectares of harvested land and a yield of 799 million tonnes in 2023, according to the Food and Agriculture Organization of the United Nations (FAO, 2025). Rapid population growth – projected to reach 9.7 billion by 2050 – will require global wheat production to rise to approximately 840 million tonnes (Sharma *et al.*, 2015; United Nations, 2022; United Nations, 2024).

At present, such demands are largely met using chemical fertilisers. In 2022, global agriculture consumed 108 million tonnes of nitrogen, 41.9 million tonnes of phosphorus and 35.5 million tonnes of potassium fertilisers (FAO, 2024). However, aside from their high cost, the long-term excessive use of these fertilisers has been shown to harm the environment. They lower soil pH and may degrade its physical structure, among other adverse effects (Buthelezi and Buthelezi-Dube, 2022; Hui *et al.*, 2022; Elagamey *et al.*, 2023). In recent years, global efforts have focused on increasing the cultivated area of wheat as a staple food crop. Yet these efforts face numerous challenges, including soil degradation, desertification, epidemics, diseases and climate change (Sharma *et al.*, 2015; Langridge *et al.*, 2022). Developing countries are particularly vulnerable, as many are situated in arid and semi-arid regions such as Asia and Africa, where agriculture depends on rainfall, rendering cultivated land unstable. Therefore, unconventional, inexpensive and eco-friendly alternatives are essential for achieving sustainable wheat cultivation and ensuring food security (Erenstein *et al.*, 2022).

In this context, the pursuit of sustainable agriculture has intensified interest in leveraging biological resources to boost wheat productivity. One promising approach is the use of cyanobacteria (Chittora *et al.*, 2020; Zahra *et al.*, 2020; Gonçalves, 2021; Abo-Shady *et al.*, 2023). Cyanobacteria have existed since the early Precambrian era (Saraf *et al.*, 2021; Allaf and Peerhossaini, 2022; Kollmen and Strieth, 2022). They are ubiquitous photoautotrophic, gram-negative prokaryotes, many of which are known for their ability to fix atmospheric nitrogen, thereby reducing their nutritional demands. This adaptability allows them to inhabit a wide range of environments, including extreme conditions, from polar regions to tropical zones. They may colonise the rock crevices in deserts by relying solely on atmospheric humidity. Cyanobacteria are also found in moist soil, on tree trunks and, in some cases, in symbiotic associations with fungi, forming lichens (Trivedi *et al.*, 2010; Saraf *et al.*, 2021; Kollmen and Strieth, 2022). Moreover, these prokaryotes are known for their ability to (1) increase soil phosphate levels by dissolving the insoluble phosphorus and converting it into Phyto-available forms (Zahra *et al.*, 2020; Nawaz *et al.*, 2024; Pathak *et al.*, 2024); and (2) form symbiotic associations with plants that facilitate a more accurate and efficient nutrient supply. These associations also reduce the risk of nutrient runoff and its environmental consequences (Nur *et al.*, 2025).

Anabaena sp. Is an unbranched, filamentous, heterocystous cyanobacterium containing specialised cells known as heterocysts at regular intervals along the filament's length (Trivedi *et al.*, 2010; Zeng and Zhang, 2022; Elagamey *et al.*, 2023). Heterocysts enable diazotrophy under aerobic conditions through their internal nitrogenase enzyme, which fixes atmospheric nitrogen and reduces it to ammonium (Trivedi *et al.*, 2010; Zeng and Zhang, 2022; Allaf and Peerhossaini, 2022; Abo-Shady *et al.*, 2023; Elagamey *et al.*, 2023). Additionally, *Anabaena* sp. produces and releases various biologically active metabolites that offer potential benefits in agriculture. These include phytohormones such as auxins, gibberellins, cytokinins, abscisic acid and ethylene (Allaf and Peerhossaini, 2022; Kollmen and Strieth, 2022). Among other effects, phytohormones influence seed germination, stimulate cell division and regulate nutrient uptake, gene expression and enzyme synthesis, thereby promoting plant growth (Chamizo *et al.*, 2018; Chua *et al.*, 2019; Kollmen and Strieth, 2022; Elagamey *et al.*, 2023; Pathak *et al.*, 2024).

Due to these properties, *Anabaena* sp. has been studied as a biofertiliser and a potential alternative to chemical fertilisers. Saadatnia and Riahi (2009) reported that rice plants showed significant increases in plant height (53%), root length (66%), root

Corresponding Author: Rana Nassour 00963945910345, ranahn1985@gmail.com

fresh weight (80%), shoot fresh weight (58%), root dry weight (150%), shoot dry weight (125%), soil porosity (28%) and soil moisture (20%) when grown in a medium containing *Anabaena* sp. Additionally, there was a decrease in soil particle density (4.8%) and soil bulk density (9.8%) (Saadatnia and Riahi, 2009). Likewise, Gheda and Ahmed (2014) have investigated the effects of *Anabaena cylindrica* inoculation on soil properties, wheat germination and early growth. They reported a significant increase in soil total organic carbon, nitrogen, potassium and phosphorus contents, along with improvements in wheat germination rate, seedling length and fresh and dry weight (Gheda and Ahmed, 2014). In addition, the findings of Kholssi *et al.* (2022) showed that applying *A. cylindrica* biomass increased the shoot dry weight of wheat by 40% (Kholssi *et al.*, 2022).

In this study, we aim to examine the effect of *A. variabilis* as a biofertiliser and growth enhancer for two local bread wheat cultivars, with a focus on photosynthetic pigments and carbohydrate and protein contents as key biochemical parameters.

2. Materials and Methods

2.1. The Cyanobacteria Strain:

A. variabilis was obtained from the Goettingen Algal Culture Collection in Germany. It was cultivated using BG11 medium ($NaNO_3$free) (Rippka and Herdman, 1992) in the laboratories of the Plant Biology Department, Faculty of Science, Tishreen University, Latakia, Syria. The strain was incubated at 25 ± 2 / 16 ± 2 °C day/night under a14:10 light: dark cycle (2500 lux) with continuous aeration for 15 days. After this period, the optical density of the culture (OD_{750}) was 0.466, and the chlorophyll a concentration was 2.05 µg/mL.

2.2. Experiment Design:

The experiment was conducted following a completely randomised design with three replications. Two *Triticum aestivum* L. cultivars – Doma 6 (D6) and Bohoth 8 (B8) – were obtained from the General Commission for Scientific Agricultural Research, Damascus, Syria. Seeds from both cultivars were germinated for seven days in the laboratory at 25 ± 2 / 16 ± 2 °C day/night. Equal-sized seedlings were then transferred to transparent pots (12 cm in diameter, 7 cm in depth) filled with 0.5 kg of autoclaved sand. Each pot contained 10 seedlings (5 of each cultivar), with a total of 16 pots assigned to each treatment.

Three treatments (T) were applied in this study:

- T1: Control (irrigated with BG11)
- T2: Control - N (irrigated with BG11 without $NaNO_3$)
- T3: Cyanobacteria treatment (inoculated with *A. variabilis* and irrigated with BG11 without $NaNO_3$)

Each pot was irrigated daily with 15 ml of the respective treatment. After planting, all pots were maintained in the laboratory at 25 ± 2 / 16 ± 2°C day/night with a14:10 light: dark cycle (2500 lux). Plant parameters were recorded at 14-, 21-, 28- and 35-day-old seedlings, using three random replicates for each parameter. These measurement stages were designated as M1, M2, M3 and M4, respectively (Figure 1).

2.3. Physiological Parameters:

Photosynthetic pigments: Samples were taken from the shoots, placed in a mortar, and ground with 10 ml of 80% acetone. The mixture was centrifuged (Heraeus Christ GMBH) at 6000 rpm and 4°C for 10 minutes. The absorbance of the supernatant was measured using a UV/VIS spectrophotometer (SECOMAM). Chlorophyll and carotenoid (Car.) contents were estimated according to Lichtenthaler and Wellburn (1983) using the following equations:

$C_{Chl.a} = 12.21A_{663} - 2.81A_{646}$

$C_{Chl.b} = 20.13A_{646} - 5.03A_{663}$

$C_{Car.} = (1000A_{470} - 3.27C_{Chl.a} - 104C_{Chl.b})/229$

For converting µg ml^{-1} values into mg g^{-1} fresh weight, the following equation was used:

mg g^{-1} FW = (µg ml^{-1} x final acetone volume (ml))/ (Fresh weight of shoots (g)*1000)

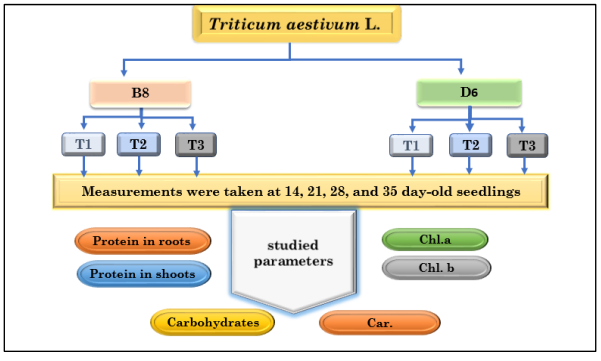
Total carbohydrate content: Carbohydrate content was estimated using anthrone reagent, based on the Lo and Garceau (1975) method. One hundred milligrams of fresh shoot tissue were ground in a mortar with 5 ml of 80% ethanol. The mixture was centrifuged (Heraeus Christ GMBH) at 6000 rpm and 4°C for 10 minutes (this step was repeated three times). The supernatant was collected and made up to 25 ml with 80% ethanol. A 0.5 ml aliquot of the resulting mixture was transferred into a clean test tube and evaporated in an oven (Heraeus D-6450) at 70°C. One millilitre of distilled water was added to the dry residue, followed by 5 ml of anthrone reagent (2 g anthrone per litre of concentrated sulphuric acid), and mixed gently. The tubes were then incubated in a hot water bath at 80°C for 10 minutes and cooled to room temperature. The absorbance was measured at 620 nm using the spectrophotometer, and carbohydrate content was calculated based on a standard glucose curve.

Protein content: Protein content in shoots and roots was estimated using a biuret reagent based on Kaplan's (1995) method. Samples were taken from shade-dried shoots and roots, then ground in a mortar under liquid nitrogen, with a 1:10 w/v Tris HCl solution (Sigma-Aldrich®) The mixture was homogenised to a uniform suspension and centrifuged at 10,000 rpm and 4°C for 20 minutes. The supernatant was purified using ammonium sulphate and centrifuged again under the same conditions. In a clean test tube, 5 ml of biuret reagent (Sigma-Aldrich®) was added to 1 ml of the resulting supernatant and mixed gently. The absorbance was measured at 540 nm using the spectrophotometer. Protein content was estimated using a standard curve of bovine serum albumin (BSA) (Sigma-Aldrich®).

2.4. The statistical Study:

All data were first checked for normality and homogeneity of variance using the Kolmogorov-Smirnov and Shapiro-Wilk tests, the normal Q-Q plot, and the test of homogeneity of variance (at $P \geq 0.05$). Levene's test of equality of error variances was also performed to confirm that all variable data were normally distributed. Each parameter was analysed using IBM SPSS Statistics v.27.0.1 via a two-way ANOVA test ($P \leq 0.05$), with treatments (T1, T2 and T3) and cultivars (D6 vs B8) as the predictors. Means were compared using Duncan's and Levene's tests.

Figure 1. Experiment Design



3. Results

3.1. The Statistical Analysis:

The statistical analysis showed significant differences between cultivars ($P \leq 0.05$), with D6 being the superior cultivar in all the studied parameters. In addition, the results of the T3 treatment were better than T1 for both cultivars, while T2 consistently showed the lowest values throughout the experiment stages (M1, M2, M3 and M4), except at M1. At that stage, no significant differences were found in Chl.a, Chl.b and Car. Contents for either cultivar across all treatments (Table 1).

Table 1. The effect of *A. variabilis* inoculation on biochemical parameters of bread wheat seedlings

Treatment		Chl.a (mg/g)			Chl.b (mg/g)			Car. (mg/g)			Carbohydrate (mg/g)			Protein in shoots (mg/g)			Protein in roots (mg/g)		
		D6	B8	Mean	D6	B8	Mean	D6	B8	Mean	D6	B8	Mean	D6	B8	Mean	D6	B8	Mean
Day 14	T1	1.08	1.02	1.05^{c}	0.24	0.21	0.22^{c}	0.014	0.012	0.013^{b}	13.22	12.16	12.69^{b}	0.99	0.88	0.94 a	0.27	0.23	0.25^{a}
	T2	1.06	1.01	1.03^{c}	0.22	0.19	0.21^{c}	0.013	0.011	0.012^{c}	9.22	8.36	8.79^{c}	0.96	0.79	0.87 b	0.26	0.22	0.24^{b}
	T3	1.12	1.09	1.105^{a}	0.26	0.22	0.24^{a}	0.015	0.013	0.014^{a}	14.08	12.48	13.28^{a}	1.02	0.89	0.96 a	0.30	0.24	0.27^{a}
	Mean (cultivars)	1.08^{a}	1.04^{a}		0.24^{a}	0.21^{a}		0.014^{a}	0.012^{a}		12.17^{a}	11.00^{b}		0.99^{a}	0.85^{b}		0.28^{a}	0.23^{b}	
Day 21	T1	1.91	1.89	1.90^{a}	0.26	0.23	0.25^{b}	0.015	0.012	0.014 a-b	14.45	13.87	14.16^{b}	1.18	0.93	1.05^{b}	0.49	0.36	0.43^{b}
	T2	1.04	0.99	1.02^{b}	0.23	0.18	0.20^{c}	0.014	0.011	0.012^{b}	8.87	7.84	8.35^{c}	0.91	0.73	0.82^{c}	0.29	0.20	0.25^{c}
	T3	1.95	1.95	1.95^{a}	0.31	0.29	0.30^{a}	0.019	0.013	0.016^{a}	15.73	14.93	15.33^{a}	1.29	0.97	1.13^{a}	0.58	0.39	0.49^{a}
	Mean (cultivars)	1.62^{a}	1.61^{b}		0.26^{a}	0.23^{b}		0.016^{a}	0.012^{b}		13.02^{a}	12.21^{b}		1.13^{a}	0.88^{b}		0.46^{a}	0.32^{b}	
Day 28	T1	1.97	1.99	1.98^{b}	0.40	0.33	0.37^{b}	0.017	0.017	0.017^{b}	16.99	15.63	16.31^{b}	1.79	1.32	1.56^{b}	0.69	0.72	0.70^{b}
	T2	0.89	0.93	0.91^{c}	0.28	0.20	0.24^{c}	0.016	0.011	0.013^{c}	7.72	6.45	7.09^{c}	0.74	0.50	0.62^{c}	0.17	0.16	0.17^{c}
	T3	2.89	2.00	2.45^{a}	0.50	0.32	0.41^{a}	0.021	0.019	0.020^{a}	19.53	15.85	17.69^{a}	2.11	1.51	1.81^{a}	0.86	0.81	0.83^{a}
	Mean (cultivars)	1.92^{a}	1.64^{b}		0.39^{a}	0.28^{b}		0.018^{a}	0.015^{b}		14.75^{a}	12.65^{b}		1.55^{a}	1.11^{b}		0.57^{a}	0.56^{b}	
Day 35	T1	2.85	2.13	2.49^{b}	0.53	0.36	0.44^{b}	0.020	0.019	0.019^{b}	17.45	16.22	16.83^{b}	2.00	1.56	1.78^{b}	0.84	0.76	0.80^{b}
	T2	0.91	0.87	0.89^{c}	0.31	0.21	0.26^{c}	0.019	0.010	0.014^{c}	6.95	5.18	6.06^{c}	0.37	0.25	0.14^{c}	0.13	0.11	0.12^{c}
	T3	3.66	2.06	2.86^{a}	0.66	0.34	0.50^{a}	0.025	0.022	0.023^{a}	22.45	16.12	19.28^{a}	2.96	1.91	2.44^{a}	0.99	0.90	0.95^{a}
	Mean (cultivars)	2.47^{a}	1.69^{b}		0.50^{a}	0.30^{b}		0.021^{a}	0.017^{b}		15.62^{a}	12.50^{b}		1.66^{a}	1.24^{b}		0.65^{a}	0.59^{b}	

Values represent the means of three replicates

Different letters (a, b, c) in the same column indicate to significant differences; n = non-significant differences according to Duncan's multiple range test at $P \leq 0.05$.

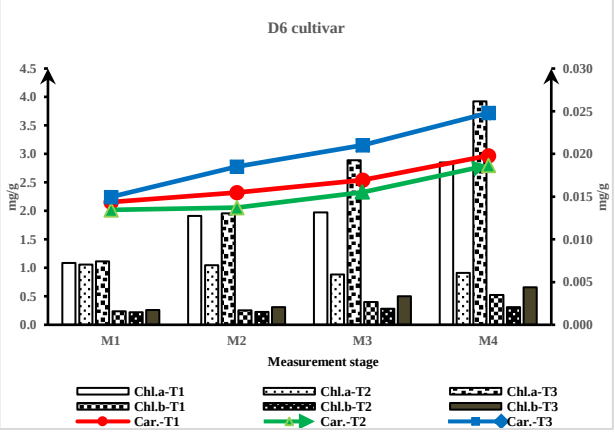
3.2. The Effect of *A. variabilis* Inoculation on Photosynthetic Pigments of Wheat Seedlings:

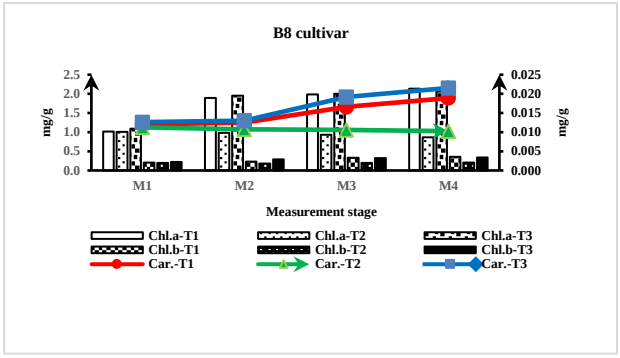
3.2.1. The Effect of *A. variabilis* Inoculation on Chlorophyll a (Chl.a) Content

Overall, Chl.a content decreased in T2 for both cultivars, with a smaller reduction observed in D6 compared to B8 (Figure 2). In D6, Chl.a declined gradually, reaching 67.96% in M4. In contrast, Chl.a in B8 under T2 declined slightly in M1 (0.41%) but then decreased sharply, reaching 59.39% in M4.

The positive effect of *A. variabilis* on Chl.a content was more evident in D6 than in B8. Chl.a levels in D6 under T3 increased consistently throughout the experiment, showing rises of 46.47% and 28.47% in M3 and M4, respectively, compared to the control. In B8 under T3, Chl.a increased only modestly compared to the control - by 7.67%, 3.17% and 0.61% in M1, M2 and M3, respectively – before decreasing by 3.49% in M4 (Figure 2).

Figure 2. The effect of *A. variabilis* inoculation on photosynthetic pigments





3.2.2. The Effect of *A. variabilis* Inoculation on Chlorophyll b (Chl.b) Content

Chl.b content decreased in D6-T2 throughout the experiment, reaching a 40.60% reduction in M4. A similar trend was observed in B8-T2, where Chl.b declined by 7.32%, 22.94%, 40.60% and 42.30% in M1, M2, M3 and M4, respectively, compared to the control (Figure 2). As for T3, Chl.b enhancement was observed in D6 compared to the control at all measurement stages, reaching 24.81% in M4. In contrast, Chl.b in B8-T3 increased in M1 and M2 (7.15% and 23.12%, respectively), followed by slight decreases in M3 and M4 (2.94% and 6.04%, respectively).

Inoculation with living cyanobacteria increased Chl.a content in B8 and Chl.b content in both D6 and B8, aligning with several previous studies (Ismail and Abo-Hamad, 2017; Gavilanes *et al.,* 2020; Kholssi *et al.,* 2022; Hakkoum *et al.,* 2025), though inconsistent with others (Matsuo *et al.,* 2022).

3.2.3. The Effect of *A. variabilis* Inoculation on Carotenoid (Car.) Content

Car. content in D6-T2 and B8-T2 decreased during the experiment, with reductions of 5.71% and 45.68%, respectively, compared to the controls (Figure 2). In contrast, Car. content in D6-T3 and B8-T3 increased compared to the controls, recording 25.22% and 14.01% increases, respectively, in M4 (Figure 2). These results are consistent with the findings of Ismail and Abo-Hamad (2017) and Hakkoum *et al.* (2025) but not with those of Matsuo *et al.* (2022).

3.3. The Effect of *A. variabilis* Inoculation on the Carbohydrate Content of Wheat Seedlings:

Carbohydrate content decreased in both cultivars under T2 treatment, with less reduction in D6 compared to B8 (Figure 3). The data showed a steep decline in carbohydrate content for D6-T2 and B8-T2, reaching 60.20% and 68.07% reductions, respectively, compared to the controls. The presence of *A. variabilis* in T3 led to a gradual increase in the carbohydrate content of D6-T3, reaching a 28.64% rise in M4 compared to the control. This steady increase was not observed in B8-T3. Instead, carbohydrate content increased in M1, M2 and M3 by 2.62%, 7.67% and 1.42%, respectively, but decreased slightly by 0.61% in M4. It is worth noting that these results are generally in line with previous research (Hakkoum *et al.,* 2025).

3.4. The Effect of *A. variabilis* Inoculation on Protein Content of Wheat Seedlings:

3.4.1. The effect of *A. variabilis* Inoculation on Protein Content in Shoots (PS)

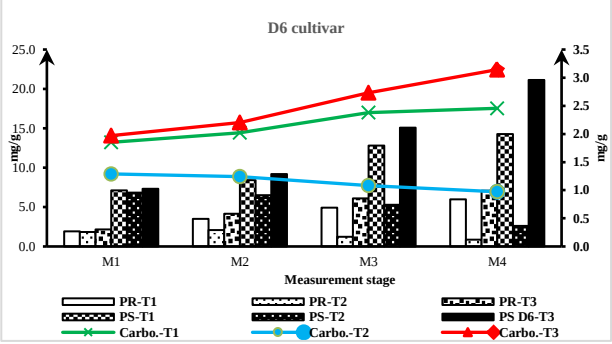
Gradual and steep drops in PS were observed in D6-T2 and B8-T2, recording 81.68% and 83.85% reductions, respectively, in the final measurement stage (M4). On the other hand, steady increases in PS were noted in D6-T3 and B8-T3. Yet, it`s worth mentioning that D6-T3 was markedly superior to B8-T3, especially at the M4 stage, with a

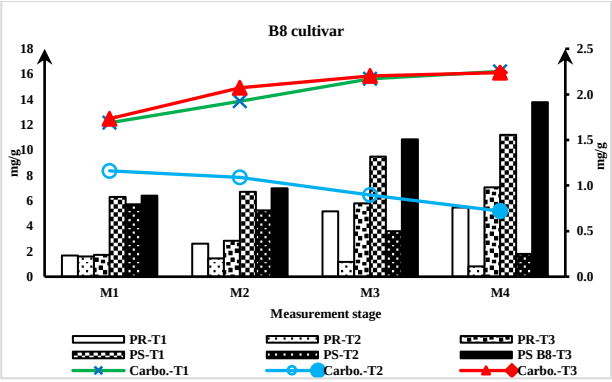
48.09% increase in D6-T3 compared to 23.04% in B8-T3 (Figure 3).

3.4.2. The Effect of *A. variabilis* Inoculation on Protein Content in Roots (PR)

PR decreased sharply in D6-T2 and B8-T2 during the experiment, recording 84.67% and 85.15% reductions, respectively, in M4 compared to the controls (Figure 3). Regarding the T3 treatment, *A. variabilis* caused a notable increase in PR, more evident in D6 compared to B8, with increases of 18.71% and 19.16%, respectively, in the M4 (Figure 3). The T3 results showed that protein content increased substantially compared to the controls, which is consistent with the findings of Ismail and Abo-Hamad (2017) and Hakkoum *et al.* (2025).

Figure 3. The effect of *A. variabilis* inoculation on carbohydrate and protein contents





4. Discussion

In the agricultural sector, nitrogen is the most essential element for plant growth and is crucial for successful cultivation in reclaimed areas (Elagamey *et al.,* 2023). Phosphorus is a key element for plant growth and development (Zahra *et al.,* 2020). Unlike conventional chemical fertilisers, biofertilisers support sustainable agriculture by promoting natural processes that contribute to soil fertility (Nur *et al.,* 2025). Nitrogen deficiency reduces the chlorophyll content in the shoots. It diminishes structural and functional proteins within chloroplasts, thereby impairing the plant's ability to carry out photosynthesis and resulting in slower growth. To cope with nitrogen deficiency, plants attempt to reallocate internal nitrogen from older tissues to younger ones due to its high mobility through the phloem. They also increase the absorption of other nutrients to maximise utilisation of the available elements. However, these compensatory mechanisms are often insufficient to restore overall plant health.

In this study, D6 and B8 did not exhibit the same positive response to the presence of *A. variabilis* in the medium, likely due to the genetic variation between the cultivars. D6 consistently showed superior levels across all measured parameters.

The results we obtained in the presence of *A. variabilis* can be attributed to its ability to:

- Increase the nitrogen availability in the soil, which promotes protein synthesis and overall plant growth. This additional nitrogen is crucial for amino acid synthesis, the building blocks of proteins.
- Stimulate the activity of various enzymes involved in metabolic processes, leading to improved nutrient assimilation and growth.
- Influence the types and amounts of proteins synthesised, potentially enhancing the nutritional quality of the wheat.
- Enhance plant chlorophyll content by improving nitrogen availability, which in turn supports both stages of photosynthesis – the light reactions and Calvin cycle – leading to greater carbohydrate production and boosting the energy available for growth and development. Additionally, *A. variabilis* may influence the metabolic pathways in wheat seedlings, potentially altering the composition of carbohydrates (e.g. increasing soluble sugar levels compared to starch).
- Stimulate root growth, leading to a more extensive root system that improves the plant's ability to absorb water and nutrients including essential minerals like nitrogen. . It also supports rhizosphere bacterial growth especially plant growth-promoting bacteria (PGPB).
- Interact with other soil microorganisms, promoting a healthy microbial community that supports plant health and nutrient cycling.
- Increase abiotic stress tolerance due to improved physiological responses, allowing plants to maintain growth under adverse conditions.
- Enhance the solubility and availability of essential nutrients in the soil and improve nutrient uptake by wheat seedlings.
- Produce and release various bioactive compounds such as:
  - Phytohormones (e.g., auxins, cytokinins) that promote plant growth and development. These hormones can enhance cell division, elongation and overall plant vigour.
  - Phenolic compounds and vitamins, which generally improve seed germination, growth and development (Chamizo *et al.,* 2018; Kollmen and Strieth, 2022).
  - Carotenoids, which are accessory pigments and play crucial roles in photosynthesis, photoprotection and phytohormone synthesis (Kollmen and Strieth, 2022; Nawaz *et al.,* 2024).
  - Phycobilins, which are closely linked to water-soluble proteins and act as accessory pigments in photosynthesis (Nawaz *et al.,* 2024).
  - Siderophores, which increase iron content in the rhizosphere, enhance iron acquisition and influence zinc mobility (Årstøl and Hohmann-Marriott, 2019; Mohan *et al.*, 2020; Nawaz *et al.,* 2024; Pathak *et al.,* 2024).
  - Exopolysaccharides, which promote soil particle aggregation, raise water retention, improve organic matter accumulation and enhance soil condition (structure and stability), thereby optimising soil fertility and plant productivity (Chamizo *et al.,* 2018; Ghazal *et al.,* 2018; Mohan *et al.*, 2020; Alvarez *et al.,* 2021; Pathak *et al.,* 2024).

Thus, applying cyanobacterial biomass is considered a sustainable, eco-friendly method that enhances crop productivity and protection due to its stimulating and fertilising potency, among other benefits (Allaf and Peerhossaini, 2022).

5. Conclusion

The results confirm the efficiency of *A. variabilis* as a promising biofertiliser for bread wheat seedlings, as it enhanced pigment and carbohydrate contents in the shoots and increased the protein content in both shoots and roots. The studied cultivars, D6 and B8 differed in their response to the presence of the cyanobacteria, with D6 showing overall superior levels across all the parameters.

Looking ahead, *A. variabilis* represents a sustainable solution to nitrogen-deficient and low-fertility land. However, further studies should be conducted to investigate its impact on the flowering, grain filling, and ripening stages, as well as to assess its effect on successive cultivation in these areas.

Data Availability Statement

The data supporting this study's findings are available on request from the corresponding author.

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Conflicts of Interest

No conflicts of interest exist.

Biographies

Rana Nassour

Department of Plant Biology, Faculty of Science, Tishreen University, Latakia, Syria, 00963945910345, ranahn1985@gmail.com

Rana earned her bachelor's degree in 2006 and her Ph.D. in 2018, both from Tishreen University in Latakia, Syria. She is a Syrian academic currently serving as a lecturer and Head of the Department of Plant Biology at the Faculty of Science, Tishreen University. Dr. Rana has published 16 research articles in various peer-reviewed journals and has taught students across all academic levels. Her work has been cited 97 times internationally, according to Google Scholar.

ORCID: 0000-0002-8883-2287.

Seraoos Mohamad

Department of Plant Biology, Faculty of Science, Damascus University, Damascus, Syria, 00963956993650, seraoosm@gmail.com

Seraoos earned his bachelor's degree from Tishreen University in Latakia, Syria, in 1999, and his Ph.D. from Damascus University in 2010. He is currently an assistant professor at the Faculty of Science, Damascus University. Dr. Seraoos has published 25 research articles in various peer-reviewed journals and has extensive experience teaching students at all academic levels.

ORCID: 0009-0008-6301-3382.

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