

Biopotential of cyanobacteria, fulvic acid and nanochitosan in controlling leaf rust of wheat

Abstract

Four biocontrol agents, including cyanobacteria, *Spirulina platensis*, and *Nostoc calcicole*, as well as fulvic acid and chitosan nanoparticles were tested to control leaf rust of wheat under field conditions during 2021/2022 and 2022/2023 growing seasons. All biocontrol agents significantly reduced all parameters for disease severity *i.e.* coefficient of infection (CI), average coefficient of infection (ACI) and area under disease progress curve (AUDPC) compared to untreated control. The best treatments were nano-chitosan which recorded efficacy of 91.17% followed by *S. platensis* (90.2%) in the application of two sprays for disease control. All biocontrol agents significantly increased grain yield components of wheat. Application of two sprays was more effective than one spray. Our study indicated that *S. platensis*, *N. calcicole*, fulvic acid and nanochitosan might be utilized for the control of wheat leaf rust disease as a safe and environmentally friendly alternative to synthetic fungicides.

Keywords: Wheat - leaf rust - Biological control - Cyanobacteria - Fulvic acid - Nano-chitosan

Introduction

Leaf rust caused by the fungus *Puccinia triticina* Eriks. is one of the most important common diseases which attack leaves of wheat (*Triticum aestivum* L.) (Huerta-Espino et al. 2011). Leaf rust can reduce grain yield of wheat by 35–50% (Abdel-Hak et al. 1980; Germán et al. 2007 and Draz et al. 2015), while in endemic regions, it can reduce yield by as much as 60% (Lesovoi et al. 1981). Generally, rust control by fungicide application is one of the most popular means of maximizing grain yield globally. Fungicides can also play a role in an integrated management of the disease until new cultivars with genetic resistance are available (Loughman et al. 2005). However, the excessive and irrational use of synthetic fungicides has perturbed us with irrevocable soil-water-air contaminations, development of resistance in microbes, and disturbing biosphere (Devi et al. 2020). Recently using biocontrol had gained considerable attention as alternative options to synthetic fungicides and efforts have been made to utilize, the biocontrol has strategies against plant diseases (Dubey et al. 2008).

Cyanobacteria, also called blue-green algae produce a wide range of bioactive compounds that are mostly used in cosmetics, animal feed, human food, nutraceutical and pharmaceutical industries, and the production of biofuels. The research concerning the use of cyanobacteria in agriculture has pointed out their potential as a source of bioactive compounds, such as phycobiliproteins, for plant pathogen control and as inducers of plant systemic resistance (Righini et al. 2022). *Arthrospira* (*Spirulina*) *platensis* is one of the

photoautotrophic, planktonic, filamentous green-blue algae (cyanobacterium) that have become of medical interest (Wollina et al. 2018). *S. platensis* extract contains phenolics that resulted in their antifungal activity (Seghiri et al. 2019; Bancalari et al. 2020; Attia et al. 2023). Spirulina was found to act as a probiotic and antioxidant agent (Abdel-Moneim et al. 2022, Abdelkhalek et al. 2015; Bhowmik et al. 2009). *S. platensis* contains high protein levels with all essential amino acids, essential fatty acids, minerals, pigments, carotenoids, and vitamins (Abdel-Moneim et al. 2022; Mendiola et al. 2007). Nostocales have been extensively studied since the early 2000. The microalgae (*Nostoc calcicole*) are more primitive than terrestrial plants and they are capable of producing relatively complex polyphenols (Ali and Doumandji 2017). Alkaloids are commonly found to have antimicrobial properties (Omulokoli et al. 1997) against both Gram-positive and Gram-negative bacteria (Cowan 1999). Extract of the cyanobacterium strain *Nostoc calcicola* HN9 expressed positive effect on growth and development, and raised soybean productivity.

Nanochitosan or chitosan nanoparticles having biocompatibility, biodegradability, wide biological activities, and ecological safety characteristics are in the forefront list of scientists (Shukla et al. 2013; Kah and Hofmann 2014; Kashyap et al. 2015). Potential of nano-chitosan as a biocontrol agent against many plant diseases, including wheat rusts has been previously reported (ElSharkawy et al. 2022; El-Khwaga et al. 2023). Fulvic acid is a plant biostimulant that are produced mainly by biodegradation of lignin containing plant organic matter (Malan, 2015). Fulvic acid has been early recorded to have an appositive effect against plant pathogens (Kamel et al. 2014; El-Sawy et al. 2016).

The present study investigated the antifungal efficacy of cyanobacteria (*Spirulina platensis*, *Nostoc calcicole*), fulvic acid and chitosan nanoparticles against wheat leaf rust and to determine the histopathologic defence mechanisms involved disease control.

Materials and Methods

Preparation of cyanobacteria

Filamentous heterocystous cyanobacteria or blue-green algae *Spirulina platensis* and *Nostoc calcicole* were obtained from Soil, Water and Environmental Research Institute, Agricultural Research Center (ARC). *S. platensis* was maintained in Zarrouk's liquid medium (Zarrouk, 1966), *N. calcicole* was maintained in BG-11 liquid medium (Rippka et al., 1979). Cultures were separately maintained in 1 L flasks with 300 mL culture medium composed of sterilized tap water. Each Flask was inoculated with 3 ml of cyanobacteria were studied, incubated at $29 \pm 2^\circ\text{C}$ under a 12h-light/12h-dark cycle with a light intensity of $156 \text{ mmol of photons s}^{-1} \text{ m}^{-2}$ and constant aeration of $4.95 \pm 0.03 \text{ mL s}^{-1}$. Manual shaking of cultures was done 3–4 times daily (Pandey et al. 2010). After 20 days, the biomass from the cultural medium was separated by filtration of culture media by filter paper Whatman No.1, and then using the filtrate output as treatment (Loaiza et al. 2016). The extracts were adjusted to a final concentration of 100 ml L^{-1} .

Preparation of Fulvic acid

Fulvic acid (FA) was obtained from Technogen Chemical Co., Egypt, and prepared according to the methods described by **Kononova (1966)**. Ten g dried powder of fulvic acid was separately extracted with distilled water (100 ml) for 24 h at room temperature. The obtained extracts were separately collected, filtered and concentrated at 40°C. Subsequently, a stock solution of fulvic acid was 100,000 ppm. The used concentration of fulvic acid was 150 µg mL⁻¹ (150 ppm).

Preparation of Chitosan Nanoparticles

Synthesis and characterisation of chitosan nanoparticles were described in our previous study of **ElKhwaga et al. (2023)** and used in the current study. The used concentration of nano-chitosan was 150 µg mL⁻¹ (150 ppm).

Biological control of wheat leaf rust

The present investigation was carried out at the Experimental Farm of El-Gemmeiza Agricultural Research Station, Agricultural Research Center, Egypt during two growing seasons 2021/2022 and 2022/2023. Four biological treatments, *Spirulina platensis*, *Nostoc calcicole*, fulvic acid chitosan nanoparticles were tested for their biopotential efficacy against wheat leaf rust disease under field conditions. A split plot design with three replicates was used to set up the experiment. Grains of the susceptible wheat cultivar (cv. Gemmeiza-7) were sown in experimental plots consisted of three rows with 3 m long and 30 cm apart received 15 g of grains/row. The main plots were represented by one- and two-sprays for each treatment. The sub plots were represented by the tested treatments. All plots were surrounded by a spreader area with a highly susceptible wheat variety (Morocco). All cultural practices recommended in the commercial fields *i.e.*, fertilization, irrigation and other management were applied. The artificial inoculation was carried out at the 7th growth stages (**Large 1954**) by using a mixture of urediniospores of *Pt* isolates according to **Tervet and Cassel (1951)**. The biological treatments were applied twice at 7-8th growth stage (**Large 1954**), using a hand sprayer until the wetness of plants. The first spray was applied 1 day before pathogen inoculation and the second spray was applied at the infection appearance (3%) (about 15 days of the first one). The fungicide (propiconazole 25%) at a rate of 0.25 ml L⁻¹ was used for comparison. The untreated control plots were sprayed with distilled water.

Disease assessment

Leaf rust scoring was quantified based on the coefficient of infection (CI) according to **Saari and Wilcoxson (1974)** and the area under disease progress curve (AUDPC) according to **Pandey et al. (1989)**. Rust scoring was assessed four times at growth stages GS 51 to GS 83, at 10 days intervals (**Zadoks et al. 1974**). The infection types were scored according to **Roelfs et al. (1992)** as resistant (R), moderately resistant (MR), moderately susceptible (MS) and susceptible (S). Rust severity was estimated as infection

percentage coverage of leaves with rust pustules using Modified Cobb's scale (**Peterson et al. 1948**). The coefficient of infection (CI) was calculated by multiplying the severity value by a constant value of 0.2, 0.4, 0.6, 0.8 and 1.0 for infection types ratings of R, MR, MR-MS, MS and S, respectively. The average coefficient of infection (ACI) was calculated as mean CI values over seasons. The AUDPC was calculated using the following equation:

$$\text{AUDPC} = D \left[\frac{1}{2} (Y_1 + Y_K) + Y_2 + Y_3 + \dots + Y_{K-1} \right]$$

where D = days between two consecutive recordings (time intervals), $Y_1 + Y_K$ = sum of the first and the last disease scores and $Y_2 + Y_3 + \dots + Y_{K-1}$ = sum of all in between scores.

The efficacy percentage of treatment was determined according to **Rewal and Jhooty (1985)**: using the following equation:

$$\text{Efficacy} = c - t/c \times 100$$

where c = infection in control, while t = infection in treatment.

At harvest, the effects of treatments on grain yield components in terms of spike weight, 1000-kernel weight, and volume weight were estimated.

Scanning electron microscope (SEM)

Leaf specimens of leaf rust infected wheat and other treated with the tested biological agents, were harvested using sterilized scissors at 1 day post inoculation (dpi) for scanning electron microscopy investigation. Sample preparation for SEM examination was carried out as described by **Harley and Ferguson (1990)**. The SME assay was carried out using a Jeol scanning electron microscope at the National Research Center, Egypt. Ultra-structural changes on the urediniospores of *P. triticina* were investigated in treatments and untreated control.

Statistical analysis:

Data were subjected to the analysis of variance (ANOVA) using the SAS Statistical Analysis System package v.22 (SAS Institute, Cary, NC, US). Means of data were separated at the least significant difference (LSD) test at $P \leq 0.05$ (**Steel and Torrie, 1980**).

Results

Potential of biocontrol agents to control wheat leaf rust

Biopotential of cyanobacteria, fulvic acid and nano-chitosan to control leaf rust of wheat (cv. Gemmeiza-7) was tested under field conditions during 2021/22 and 2022/23 growing seasons. Data in Table (1) showed significant differences in leaf rust assessments CI, ACI and AUDPC between treatments, sprays and seasons, while interactions between them were insignificant.

Leaf rust assessments CI, ACI and AUDPC were significantly reduced due to biological treatments compared to untreated control. Application of two sprays was better than one spray for all treatments showing high significant differences. In the calculated means for biological treatments, the lowest values of ACI and AUDPC were recorded with nano-chitosan which recorded ACI values of 14.33 and 7.5, while AUDPC values of 122 and 61.83 for one and two sprays, respectively. Cyanobacterium *S. platensis* ranked second with ACI of 17 and 8.33, and AUDPC of 131.66 and 65.66, followed by fulvic acid with ACI of 24.33 and 8.33, and AUDPC of 192.83 and 67.66 for one and two sprays, respectively. The aforementioned treatments were comparable to fungicide (propiconazole 25%) which recorded ACI of 13.66 and 5.33, and AUDPC of 91.33 and 50.33 for one and two sprays, respectively. Cyanobacterium *N. calcicole* also significantly reduced ACI to 25 and 16.66, and AUDPC to 204.16 and 121.83 for one and two sprays, respectively, as compared to untreated control with ACI of 85 and AUDPC of 915.

Table 1 Biopotential of cyanobacteria, fulvic acid and nano-chitosan to control leaf rust of wheat (cv. Gemmeiza-7) under field conditions during 2021/22 and 2022/23 growing seasons.

Treatment	CI				ACI		AUDPC				Mean AUDPC	
	1 st season		2 nd season		Sp ¹	Sp ²	1 st season		2 nd season		Sp ¹	Sp ²
	Sp ¹	Sp ²	Sp ¹	Sp ²			Sp ¹	Sp ²	Sp ¹	Sp ²		
<i>Spirulina platensis</i>	17.33	8.33	16.33	8.33	17	8.33	134	67.66	129.33	63.66	131.66	65.66
<i>Nostoc calcicole</i>	26.66	16.66	23.33	16.66	25	16.66	205	124	203.33	119.66	204.16	121.83
Fulvic acid	26.66	8.33	22	8.33	24.33	8.33	195.66	70.33	190	65	192.83	67.66
Nanochitosan	15.33	8.33	13.33	6.66	14.33	7.5	124	64	120	59.66	122	61.83
Propiconazole	14	5.33	13.33	5.33	13.66	5.33	94.33	52	88.33	48	91.33	50.33
Control	86.66		83.33		85		980		850		915	
LSD _{0.05} Treatment (T)	6.34		6.16		5.86		7.62		6.14		6.7	
LSD _{0.05} Spray (Sp)	4.12		4		1.63		2.41		2.32		0.94	
LSD _{0.05} Season (S)					2.18						2.5	
LSD _{0.05} T × S					Ns						ns	
LSD _{0.05} T × S × Sp					Ns						ns	

CI = coefficient of infection, ACI = average coefficient of infection (ACI), AUDPC = area under disease progress curve, *r*-AUDPC = relative AUDPC, Sp¹= one spray, Sp²= two sprays

Efficacy of biocontrol agents against wheat leaf rust

Figure (1) showed that all the tested biocontrol agents were effective to control leaf rust where the efficiency ranged from 70.58 to 83.14% and 80.04 to 91.17% for one and

two spray, respectively. Nanochitosan was the most effective treatment (83.14, 91.17%), followed by cyanobacterium; *S. platensis* (80, 90.2%), and fulvic acid (71.37, 90.2%) for one and two sprays, respectively. The aforementioned treatments were comparable to fungicide (propiconazole 25%) which recorded 84.31 and 93.72% efficacy. Application of *N. calcicole* also showed efficacy of 70.58 and 80.4% for one and two sprays, respectively.

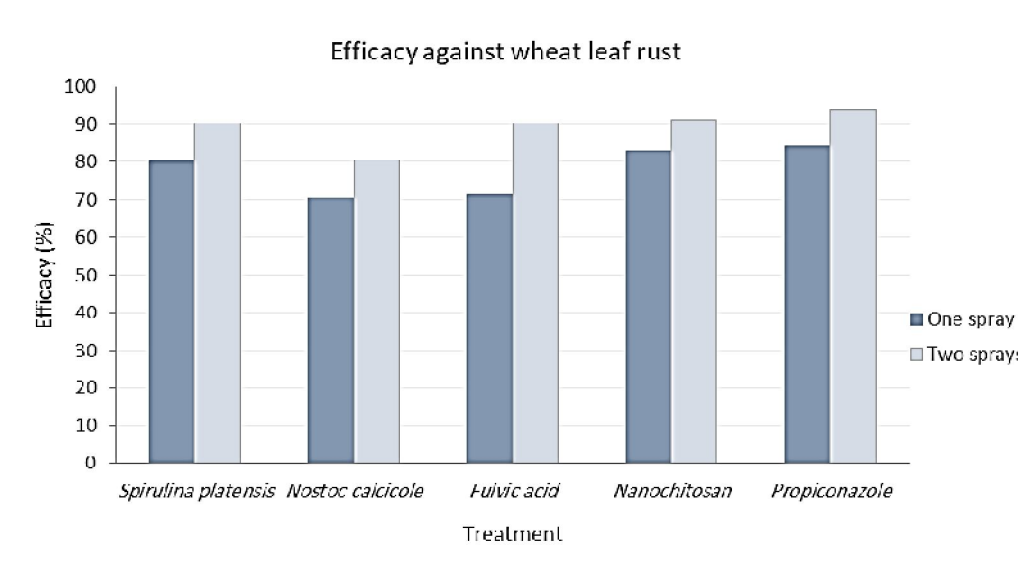


Fig. (1) Efficacy of cyanobacteria, fulvic acid and nano-chitosan to control leaf rust of wheat (cv. Gemmeiza-7) under field conditions.

Effect of biocontrol agents on grain yield components

Data in Table (2 and 3) showed that all biocontrol agents significantly increased the grain yield components in terms of spike weight, 1000-kernel weight, and volume weight in comparison to the untreated control during both growing seasons 2021/22 and 2022/23. High significant differences were recorded between the treatments and untreated control. Nanochitosan recorded the highest weights of grain yield components followed by *S. platensis* and fulvic acid during both seasons. Data in the first season (Table 2) showed that nanochitosan recorded spike weight of 4.13, 4.42 g and 1000-kernel weight of 57.36, 62.42 g, volume weight of 710.53, 721.54 g L⁻¹, followed by cyanobacterium *S. platensis* 3.85, 3.95 g spike weight, 50.6, 54.20 g 1000-kernel weight, and 689.56, 695.14 g L⁻¹ volume weight for one and two sprays, respectively. Data in the second season (Table 3) showed that nanochitosan recorded 4.18, 4.50 g spike weight and 59.41, 62.78 g 1000-kernel weight and 711.33, 722.42 g L⁻¹ volume weight, followed by cyanobacterium *S. platensis* with 3.87, 3.98 g spike weight, 50.61, 54.32 g 1000-kernel weight and 689.56, 695.14 g L⁻¹ volume weight for one and two sprays, respectively. The aforementioned treatments were comparable to fungicide propiconazole 25% during both seasons. Grain yield components associated with application of *N. calcicole* were also significantly increased during both seasons as compared to untreated control.

Table 2 Grain yield components of wheat (cv. Gemmeiza-7) treated with cyanobacteria, fulvic acid and nanochitosan against leaf rust under field conditions during 2021/22 growing season.

Treatment	Spike weight (g)		1000-kernel weight (g)		Volume weight g L ⁻¹	
	Sp ¹	Sp ²	Sp ¹	Sp ²	Sp ¹	Sp ²
<i>Spirulina platensis</i>	3.85	3.95	50.6	54.20	689.56	695.14
<i>Nostoc calcicole</i>	3.77	3.87	46.66	49.80	675.45	682.57
Fulvic acid	3.90	4.00	50.42	55.15	690.52	702.11
Nanochitosan	4.13	4.42	57.36	62.42	710.53	721.54
Propiconazole	4.10	4.35	55.64	61.28	710.50	718.22
Control	3.05		40.45		630.11	
LSD _{0.05} Treatment (T)	0.16		1.2		5.62	
LSD _{0.05} Spray (Sp)	0.12		0.84		3.15	
LSD _{0.05} T × Sp	0.8		Ns		ns	

Sp¹ = one spray, Sp² = two sprays

Table 3 Grain yield components of wheat (cv. Gemmeiza-7) treated with cyanobacteria, fulvic acid and nanochitosan against leaf rust under field conditions during 2022/23 growing season.

Treatment	Spike weight (g)		1000-kernel weight (g)		Volume weight g L ⁻¹	
	Sp ¹	Sp ²	Sp ¹	Sp ²	Sp ¹	Sp ²
<i>Spirulina platensis</i>	3.87	3.98	50.61	54.32	689.56	695.14
<i>Nostoc calcicole</i>	3.80	3.88	46.68	49.85	675.45	684.21
Fulvic acid	3.93	4.02	50.64	55.35	690.52	702.11
Nanochitosan	4.18	4.50	59.41	62.78	711.33	722.42
Propiconazole	4.15	4.37	55.75	61.60	710.78	719.54
Control	3.17		41.53		632.24	
LSD _{0.05} Treatment (T)	0.21		1.06		4.97	
LSD _{0.05} Spray (Sp)	0.18		0.92		3.23	
LSD _{0.05} T × Sp	0.65		Ns		ns	

Sp¹ = one spray, Sp² = two sprays

Scanning electron microscope (SEM)

Figure (2) illustrated urediniospore observation using SEM of urediniospores of *P. triticina* on adult plant leaves of wheat (Gemmeiza-7) treated with biological agents, *Spirulina platensis*, *Nostoc calcicole*, fulvic acid and nano-chitosan, as compared to fungicide propiconazol 25% and untreated control. All biological agents inhibited spore germination, while abundant germination was observed in untreated control. Fungicide (propiconazol 25%) also reduced spore germination. The non-germinated urediniospores were observed to be shrivelled by application of *S. platensis* and *N. calcicole*, (Fig. 2, A, B). Change in shape of non-germinated urediniospores from round to oval were observed by application of fulvic acid and nano-chitosan (Fig. 2, C, D). Swelling of germinated urediniospores were observed by application of fungicide propiconazole 25% (Fig. 2, E). In untreated control, normal shape of germinated urediniospores and germ tubes were observed along with appressorium formation (Fig. 2, F).

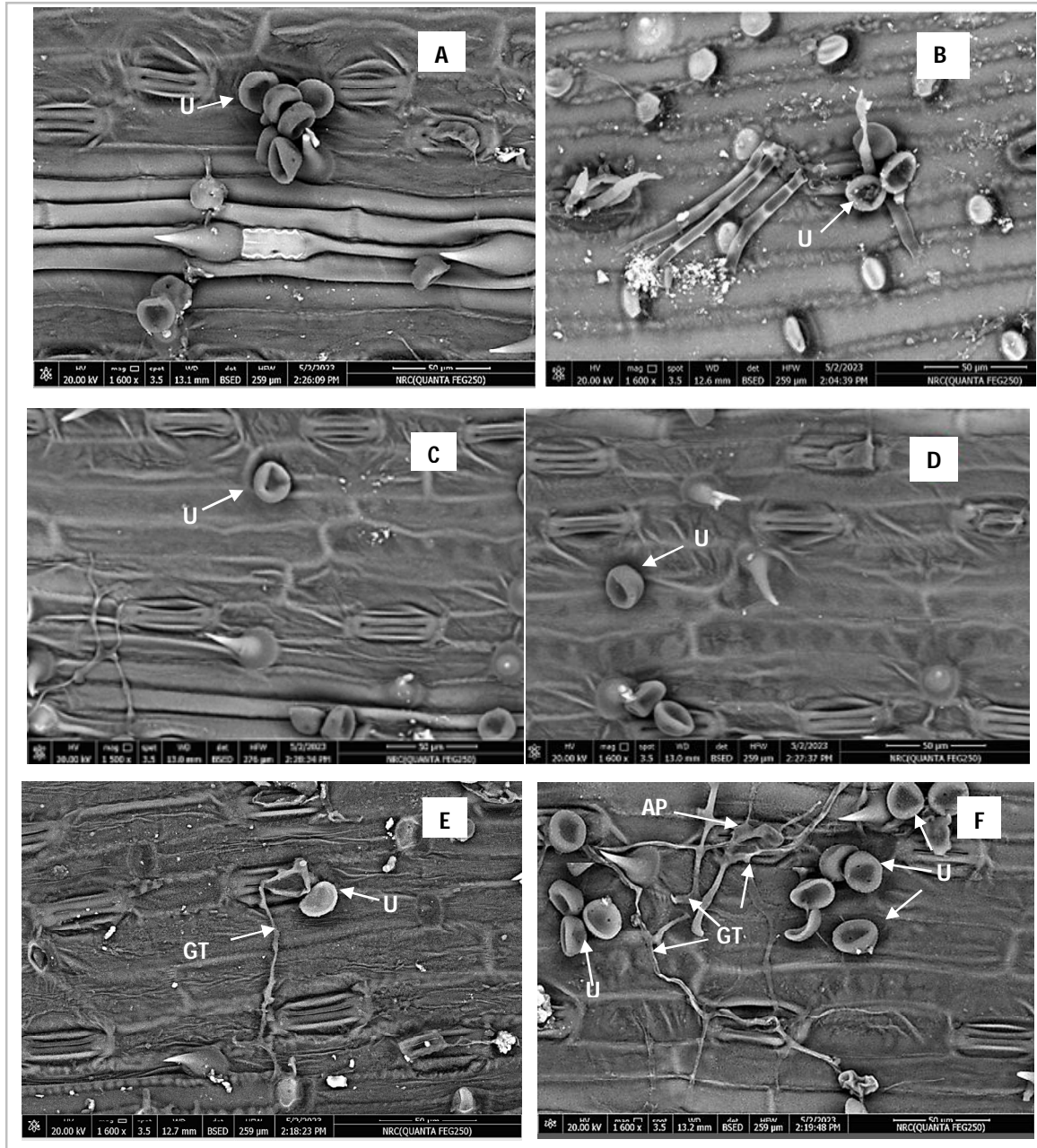


Figure (2): SEM observation of *P. tritici* urediniospores on adult plant leaves of wheat (Gemmeiza-7) treated with biological agents, *Spirulina platensis* (A), *Nostoc calcicole* (B), Fulvic acid (C), nanochitosan (D), Fungicide propiconazole 25% (E), and untreated control (F). U: Urediniospore, GT: Germ tube, AP: appressorium.

Discussion

Eco-friendly control of plant diseases using biological agents which act directly on the plant pathogens in plants, have gained considerable attention as alternative means to synthetic fungicides (Kamel et al. 2014; El-Sharkawy et al. 2022). Using natural biological material in the control of wheat rusts is a modern, advanced and risk-free alternative method of rust management (Jarvis 1988). Cyanobacteria, *Spirulina platensis* and *Nostoc calcicole* as well as fulvic acid and nanochitosan, are among the biological control agents that directly affect the phytopathogens (Malan 2015; Hassan and Chang 2017; Abdel-Moneim et al. 2022; El-Sharkawy et al. 2022). In current study, we tested the biopotential of *S. platensis*, *N. calcicole*, fulvic acid and nano-chitosan to control leaf rust of wheat (cv. Gemmeiza-7) during two growing seasons. All biocontrol agents tested significantly reduced the CI, ACI and AUDPC as compared to fungicide (propiconazole 25%) and untreated control. The best treatment was nanochitosan, followed by cyanobacterium *S. platensis* and fulvic acid. Application of *N. calcicole* also significantly reduced CI, ACI and AUDPC as compared to untreated control. The tested biocontrol agents showed high efficacy in controlling wheat leaf rust which reached 91.17% in nanochitosan, followed *S. platensis* and fulvic acid (90.2% each) for two sprays. Efficacy of *N. calcicole* against wheat leaf rust was 80.4% for two sprays.

Chitosan nanoparticles reduce spore germination and increase latency and periods of incubation meanwhile, decrease the type of infection, size, and pustules number compared to the untreated control (Elsharkawy et al., 2022). Chitosan nanoparticles have a potent antimicrobial effect due to their ability to bind microbial proteins and produce cell membrane permeability and disintegration (Juven et al., 1994). Chitosan effects on hyphal development of plant pathogens (Xu et al. 2007). In pursuit of this, chitosan, β -(1,4)-2-amino-2-deoxy-d-glucose, a hetero-aminopolysaccharide which can easily be obtained from the waste produce of shrimp, crab shells, and cell wall of fungi (Katiyar et al. 2015; Malerba and Cerana 2016). In anatomical examinations, chitosan nanoparticles enhanced thickness of blade (μ), thickness of mesophyll tissue, thickness of the lower and upper epidermis and bundle length and width in the midrib compared to the control. In the control treatment's top epidermis, several sori and a large number of urediniospores were found. Nanochitosan has been previously proven to induce resistance against leaf rust in Egypt (Elkhwaga et al. 2023; Elsharkawy et al. 2022). Fulvic acid is plant biostimulant that are produced mainly by biodegradation of lignin containing plant organic matter. Application of fulvic acid to plants affects cell membranes, leading to enhanced transport of minerals, improved protein synthesis, plant hormone like activity, promoted photosynthesis, modified enzyme activities, solubilization of micro and macro elements, reduction of active levels of toxic minerals, and increased microbial populations (Li et al. 2017). In general, fulvic acid substances are a suspension based on potassium humates which can be applied successfully in many areas of plant production as a plant growth stimulant or soil conditioner for enhancing natural resistance against plant diseases and pests (Scheuerell and Mahaffee 2004, 2006). Foliar application of fulvic acid improved plant growth and yield quantity and

quality as well as controlling powdery and downy mildews of cucumber plants (**Kamel et al 2014**). Fulvic acid has the advantage as effective and environmentally friendly agent.

The use of *Spirulina*-based stimulators is reliable with the concept of sustainable agriculture by enhancing photosynthetic pigment content and rate ensuring the correlation between the yield and those measured parameters. *Spirulina platensis* extract contains Phenols that resulted in their antifungal activity (**Seghiri et al. 2019; Bancalari et al. 2020; Attia et al. 2023**). The promotion of growth could be attributed to the nutrients, bioactive molecules and phytohormones in the *Spirulina* extract (**Shedeed et al. 2022**). Nostocales have been extensively studied since the early 2000. *Nostoc* spp. inhibited *Aspergillus* spp. mycelial growth in agar disk diffusion assay (**El-Sheekh et al. 2006, 2022; Pawar et al. 2008; Shishido et al. 2015**). Reduction in growth of *Fusarium* species was reported with *Nostoc* spp. (**El-Sheekh et al. 2006; Kim 2006; Kim and Kim 2008**). Phenols and polysaccharides contained in extracts from *Nostoc* spp. are involved in the antifungal activity against *R. solani* (**Osman et al. 2011**). In the current study, scanning electron microscope showed that all biological agents inhibited spore germination, while abundant germination was observed in untreated control. Fungicide (propiconazol 25%) also reduced spore germination.

Recently, these materials have gained considerable attention as alternative options to synthetic fungicides and efforts have been made to utilize, these material in the control strategies against plant diseases. In the current study these materials showed efficacy in controlling the leaf rust disease of wheat that was comparable to fungicide (propiconazole 25%). In experiment, wheat plants were one- and two-time sprayed with those materials. All biological control agents tested in current study significantly enhanced the grain yield components. Furthermore, the two sprays application was more effective than the one spray.

Conclusion

Application of cyanobacteria, *Spirulina platensis* and *Nostoc calcicole* as well as fulvic acid and nanochitosan, as biological control agents showed directly effect on wheat leaf rust. They had the efficacy to reduce CI, ACI and AUDPC of wheat leaf rust under field conditions. They also significantly increased grain yield components of wheat. Our study indicated that the tested bio-control agents might be utilized for the control of wheat leaf rust disease as a safe and environmentally friendly alternative to synthetic fungicides.

References

Abdel-Hak, T. M., El-Sherif, N. A., Bassiony, A.A., Shafik, I. I. and El-Douadi, Y. (1980) Control of wheat leaf rust by systemic fungicides. In: Proceedings of the 5th European and Mediterranean cereal rusts conference. Bari, Italy. 255-266

Abdelkhalek, N.K., Ghazy, E.W., Abdel-Daim M.M. (2015) Pharmacodynamic interaction of *Spirulina platensis* and deltamethrin in freshwater fish Nile

tilapia, *Oreochromis niloticus*: impact on lipid peroxidation and oxidative stress Environ. Sci. Pollut. Res., 22 pp. 3023-3031.

Abdel-Moneim, A. M. E., El-Saadony, M. T., Shehata, A. M., Saad, A. M., Aldhumri, S. A., Ouda, S. M., & Mesalam, N. M. (2022). Antioxidant and antimicrobial activities of *Spirulina platensis* extracts and biogenic selenium nanoparticles against selected pathogenic bacteria and fungi. Saudi Journal of Biological Sciences, 29(2), 1197-1209.

Ali, I. H., Doumandji, A. (2017). Comparative phytochemical analysis and in vitro antimicrobial activities of the cyanobacterium *Spirulina platensis* and the green alga *Chlorella pyrenoidosa*: potential application of bioactive components as an alternative to infectious diseases. Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Vie, 39, 41-49.

Attia M.S., Elsayed S.M., Abdelaziz A.M., Ali M.M. (2023) Potential impacts of *Ascophyllum nodosum*, *Arthrospira platensis* extracts and calcium phosphite as therapeutic nutrients for enhancing immune response in pepper plant against *Fusarium* wilt disease. Biomass Conv. Bioref. <https://doi.org/10.1007/s13399-023-03949-9>

Bancalari E, Martelli F, Bernini V, Neviani E, Gatti M (2020) Bacteriostatic or bactericidal? Impedometric measurements to test the antimicrobial activity of *Arthrospira platensis* extract. Food Control 118:107380. <https://doi.org/10.1016/j.foodcont.2020.107380>

Bhowmik, D., Dubey, J., Mehra, S. (2009), Probiotic efficiency of *Spirulina platensis*-stimulating growth of lactic acid bacteria. World J. Dairy Food Sci., 4 pp. 160-163.

Cowan M.M., 1999. Plant products as antimicrobial agents. Clinical Microbiology Reviews, 12, 564-582.

Devi, K. A., Prajapati, D., Kumar, A., Pal, A., Bhagat, D., Singh, B. R., ... & Saharan, V. (2020). Smart Nano-Chitosan for Fungal Disease Control. In *Nanopesticides* (pp. 23-47).

Elkhwaga, A. A., Eldakar, H. A., Alkollaly, A. M., Draz, I. S., & Abdelghany, R. E. (2023). Nanochitosan and water-soluble vitamins induce resistance to leaf rust and related metabolism in wheat. Egyptian Journal of Phytopathology, 51(1), 65-75.

El-Sawy, M. M.; Omara, R. I. Ashmawy, M. A. (2016). Use of natural products as fungicide alternatives against wheat stripe rust and improvement grain crop. Egypt J. Plant Pro. Res. 4 (4): 1-20 (2016)

Elsharkawy, M.M.; Omara, R.I.; Mostafa, Y.S.; Alamri, S.A.; Hashem, M.; Alrumman, S.A. and Ahmad, A.A. 2022. Mechanism of wheat leaf rust control using chitosan nanoparticles and salicylic acid. J. Fungi, 8(3): 304.

El-Sheekh, M. M., Deyab, M. A., Hasan, R. S., Abu Ahmed, S. E., & Elsadany, A. Y. (2022). Biological control of Fusarium tomato-wilt disease by cyanobacteria *Nostoc* spp. *Archives of Microbiology*, 204(1), 1-14.

El-Sheekh, M.M.; Osman, M.E.H.; Dyab, M.A.; Amer, M.S. (2006) Production and characterization of antimicrobial active substance from the cyanobacterium *Nostoc muscorum*. *Environ. Toxicol. Phar.* 21:42–50.

Hassan, O., Chang, T. (2017). Chitosan for eco-friendly control of plant disease. *Asian J. Plant Pathol*, 11(2), 53-70.

Huerta-Espino, J., Singh, R. P., German, S., McCallum, B. D., Park, R. F., Chen, W. Q., Bhardwaj, S. C. and Goyeau, H. (2011) Global status of wheat leaf rust caused by *Puccinia triticina*. *Euphytica*, 179, 143-160.

Kah M, Hofmann T (2014) Nanopesticide research: current trends and future priorities. *Environ Int* 63:224–235.

Kamel, S. M., Afifi, M. M., El-shoraky, F. S., El-Sawy, M. M. (2014). Fulvic acid: a tool for controlling powdery and downy mildews in cucumber plants. *International Journal of Phytopathology*, 3(2), 101-108.

Kashyap PL, Xiang X, Heiden P (2015) Chitosan nanoparticle based delivery systems for sustainable agriculture. *Int J Biol Macromol* 77:36–51.

Katiyar D, Hemantaranjan A, Singh B (2015) Chitosan as a promising natural compound to enhance potential physiological responses in plant: a review. *Indian J Plant Physiol* 20(1):1–9

Kim, J.; Kim, J.-D. (2008) Inhibitory effect of algal extracts on mycelial growth of the tomato-wilt pathogen, *Fusarium oxysporum* f. sp. *lycopersici*. *Mycobiology* 36:242–248.

Kim, J.D. (2006) Screening of cyanobacteria (blue-green algae) from rice paddy soil for antifungal activity against plant pathogenic fungi. *Microbiology* 34:138–142.

Kononova, M. M. 1966. Soil Organic Matter. Pergamon Press Oxford, London, Edinburgh, New York, pp. 544.

Large E.C. (1954), Growth stages in cereals. Illustration of the Feekes scale. *Plant Pathology*, 3: 128-129. <https://doi.org/10.1111/j.1365-3059.1954.tb00716.x>

Li, W., Zhang, F., Ye, Q., Wu, D., Wang, L., Yu, Y., ... Du, J. (2017). Composition and copper binding properties of aquatic fulvic acids in eutrophic Taihu Lake, China. *Chemosphere*, 172, 496-504.

Loaiza, N.R., Vera, P., Aiello-Mazzarri, C., Morales, E. (2016). Comparative growth and biochemical composition of four strains of *Nostoc* and *Anabaena* (Cyanobacteria,

Nostocales) in relation to sodium nitrate. *Acta Biológica Colombiana*, 21(2):347-354. <https://doi.org/10.15446/abc.v21n2.48883>

Loughman, R; Jayasena, K; Majewski, J (2005). Yield loss and fungicide control of stem rust of wheat. *Aust. J. Agric. Res.* 56:91-96.

Malan, C. (2015). Review: humic and fulvic acids. A Practical Approach. In *Sustainable soil*

Malerba M, Cerana R (2016) Chitosan effects on plant systems. *Int J Mol Sci* 17(7):996.

Mendiola, J. A., Jaime, L., Santoyo, S., Reglero, G., Cifuentes, A., Ibañez, E., Señoráns, F. J. (2007). Screening of functional compounds in supercritical fluid extracts from *Spirulina platensis*. *Food chemistry*, 102(4), 1357-1367.

Omulokoli E., Khan B., Chhabra S. (1997). Antiplasmodial activity of four Kenyan medicinal plants. *J. Ethnopharmacol.*, 56, 2, 133-137.

Osman, M.E.A.H.; El-Sheekh, M.M.; Metwally, M.A.; Ismail, A.E.W.A.; Ismail, M.M. Antagonistic activity of some fungi and cyanobacteria species against *Rhizoctonia solani*. *Int. J. Plant Pathol.* **2011**, 2, 101–114.

Pandey JP, Neeraj P, Tiwari A (2010) Standardization of pH and light intensity for the biomass production of *Spirulina platensis*. *J Algal Biomass Utln* 1(2):93–102

Pandey, H. N., Menon, T. C. M., & Rao, M. V. (1989). A simple formula for calculating area under disease progress curve. *Barley and Wheat Newsletter*.

Pawar, S.T.; Puranik, P.R. (2008) Screening of terrestrial and freshwater halotolerant cyanobacteria for antifungal activities. *World J. Microbiol. Biotechnol.* 24:1019–1025.

Peterson, R. F., Campbell, A. B. and Hannah, A. E. (1948) A diagrammatic scale for estimating rust intensity on leaves and stems of cereals. *Canadian Journal of Research*, 26, 496-500.

Rewal, H. S. and Jhooty, J. S. (1985) Differential response of wheat varieties to systemic fungitoxicants applied to *Ustilago tritici* (Pers.). *Rostr. Indian Journal of Agricultural Sciences*, 55, 548-9.

Righini H, Francioso O, Martel Quintana A, Roberti R. (2022) Cyanobacteria: A natural source for controlling agricultural plant diseases caused by fungi and oomycetes and improving plant growth. *Horticulture*8(1):58. <https://doi.org/10.3390/horticulturae8010058>

Rippka, R., J. Deruelles, J. Waterbury, M. Herdman and R. Stanier. (1979). Generic assignments, strain histories and properties of pure cultures of cyanobacteria. *J. Gen. Microbiol.* 111: 1-61.

Roelfs, A.P.; Singh, R.P. and Saari, E.E. (1992). Rust Diseases of Wheat: Concepts and Methods of Disease Management. CIMMYT, Mexico, D.F. 81 pp.

Saari EE, Wilcoxson RD (1974) Plant disease situation of high yielding durum wheat in Asia and Africa. *Annu Rev Phytopathol* 2:49 –68.

Scheuerell, S.J., W.H. Mahaffee. 2004. Compost Tea as a Container Medium Drench for Suppressing Seedling Damping-Off Caused by *Pythium ultimum*. *Phytopathology* 94: 1156-1163.

Scheuerell, S.J., W.H. Mahaffee.2006. Variability Associated with Suppression of Gray Mold (*Botrytis cinerea*) on Geranium by Foliar Applications of Nonaerated and Aerated Compost Teas. *Plant Disease* 90: 1201-1208.

Seghiri R, Kharbach M, Essamri A (2019) Functional composition, nutritional properties, and biological activities of Moroccan *Spirulina* microalga. *J Food Qual* 2019. <https://doi.org/10.1155/2019/3707219>

Shedeed, Z. A., Gheda, S., Elsanadily, S., Alharbi, K., & Osman, M. E. (2022). *Spirulina platensis* Biofertilization for Enhancing Growth, Photosynthetic Capacity and Yield of *Lupinus luteus*. *Agriculture*, 12(6), 781.

Shishido TK, Humisto A, Jokela J, Liu L, Wahlsten M, Tamrakar A, Fewer DP, Permi P, Andreote AP, Fiore MF, Sivonen K. (2015) Antifungal compounds from cyanobacteria. *Mar Drugs* 13(4):2124-40. doi:10.3390/md13042124.

Shukla SK, Mishra AK, Arotiba OA, Mamba BB (2013) Chitosan-based NMs: a state-of-the-art review. *Int J Biol Macromol* 59:46–58.

Steel, R.G.D. and Torrie, J.H. 1980. Principles and procedures of statistics, Second ed. Mc Graw Hill Book Company, New York, pp 633.

Tervet, I. W. and Cassell, R. C. (1951) The use of cyclone separation in race identification of cereal rusts. *Phytopathology*, 41, 286-290.

Wollina, U., Voicu, C., Gianfaldoni, S., Lotti, T., França, K., Tchernev, G. (2018). *Arthrospira platensis*–potential in dermatology and beyond. Open access Macedonian Journal of Medical Sciences, 6(1), 176.

Wuletaw, T; Zewdie B; Solomon, A (2018). Wheat production and breeding in sub-saharan Africa: Challenges and opportunities in the face of climate change", *International Journal of Climate Change Strategies and Management*, Downloaded on: 17 December 201.

Xu, J.; Zhao, X.; Han, X.; Du, Y. 2007. Antifungal activity of oligochitosan against *Phytophthora capsici* and other plant pathogenic fungi in vitro. *Pestic. Biochem. Physiol.*, 87(3): 220-228.

Zarrouk C. (1966). Contribution à l'étude de cyanophycees. Influence de divers facteurs physiques et chimiques sur la croissance et la photosynthèse de *Spirulina maxima* (Setch. et Gardner) Geitler. Ph D. Thesis, University of Paris, France. 310 p.

UNDER PEER REVIEW