Journal of Soil Science and Plant Nutrition (2025) 25:6720–6739
https://doi.org/10.1007/s42729-025-02559-w

ORIGINAL PAPER

Harnessing *Chlorella vulgaris* for Mucilage Mitigation and Wheat Growth on Fluvisol: A Study on Wastewater Treatment Efficacy

Muhittin Onur Akca[1] · Selen Deviren Saygin[1] · Adem Bilgin[2] · Sefika Arslan[3] · Gunay Erpul[1]

Received: 31 December 2024 / Accepted: 23 June 2025 / Published online: 30 June 2025
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Abstract
This study aimed to determine the phytoremediation efficiency of *Chlorella vulgaris* microalgae as a circular bioeconomic approach using wastewater samples from deep-sea discharge points at the Ambarlı and Pasakoy Wastewater Treatment Plants (WWTPs) in Istanbul, where mucilage formation has been a significant concern Furthermore, the potential of the produced microalgae biomass as a biofertilizer for wheat (*Triticum aestivum* L.) growth on fluvisol was assessed.Wastewater samples were collected from each WWTPs for analysis. *Chlorella vulgaris* was cultivated in BG-11 medium and used to evaluate nutrient removal efficiency over time. A greenhouse experiment was conducted to assess the effects of *Chlorella vulgaris* biomass as a biofertilizer on wheat growth, with treatments including microalgae and Diammonium Phosphate (DAP) fertilizer combinations. The results indicated that *Chlorella vulgaris* achieved the highest nitrogen (N) reduction (43.65% and 17.63%) within the first 30 min at the respective stations, while the maximum phosphorus (P) removal (75.42% and 19.16%) occurred at the end of 300 min. A 30-minute treatment period was found optimal for nutrient removal, after which the greenhouse experiment commenced. In the greenhouse experiment, microalgae treatments (0.01 g kg^{-1} and 0.04 g kg^{-1}) combined with DAP fertilizer (Chemical Fertilizer, CF: 150 kg ha^{-1}) significantly improved soil properties and plant growth parameters. However, these treatments also caused an increase in heavy metal content in soils and plants.The findings highlight that while biomass from wastewater treatment is a promising biofertilizer alternative, pre-treatment to remove adsorbed heavy metals is crucial to minimize environmental risks and unlock its agricultural potential.

Keywords Mucilage · Wastewater treatment · Microalgae · *Chlorella vulgaris* · Wheat cultivation

1 Introduction

Municipal wastewater management is a key issue for environmental sustainability (Kehrein et al. 2020). With rapid urbanization, effectively managing wastewater has become one of the most significant environmental challenges in developing countries (Qu et al. 2019). Global wastewater statistics highlight the growing need for effective treatment and reuse to meet rising demand and environmental protection goals. As of recent assessments, about 380 billion cubic meters of wastewater are discharged worldwide each year, but less than half is safely treated, leaving significant environmental and public health risks. Urban areas, home to nearly 55% of the global population, produce the bulk of this wastewater. By 2050, urbanization is expected to increase this share to 68%, and effective wastewater management will become even more critical (Jones et al. 2021).

Anthropogenic activities, such as agriculture and industrial processes, release substantial pollutants into water systems, significantly impacting surface water quality. The excessive use of chemical fertilizers, particularly N and P, has resulted in nutrient application rates doubling or tripling since the 1960s, leading to eutrophication and other ecological challenges in water management (Dagsuyu et al. 2024; Egbueri et al. 2020; Garcia-Gonzalez and Sommerfeld

✉ Muhittin Onur Akca
moakca@ankara.edu.tr

[1] Faculty of Agriculture, Department of Soil Science and Plan Nutrition, Ankara University, Ankara 06110, Türkiye

[2] Research and Development Working Group, Ministry of Agriculture and Forestry, Department of Nature Conservation, Ankara 06560, Türkiye

[3] Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Gaziosmanpaşa University, Tokat 60240, Türkiye

2016). Marine ecosystems are particularly vulnerable to eutrophication and pollution from land-based sources, which can lead to the production of mucilage. For instance, the study by Kovač et al. (2023) emphasizes the significant regulation of elemental composition within planktonic exometabolites, which are crucial for understanding the broader implications of mucilage within the global carbon narrative. The accumulation of organic waste in aquatic environments, combined with nutrient enrichment, exacerbates mucilage formation. Decomposition by bacteria, phytoplankton, and zooplankton significantly contributes to mucilage formation, as evidenced by recurrent blooms in the Bosphorus, including the severe 2021 event, which profoundly impacted marine ecosystems and local communities (Yildirim et al. 2022). The Marmara Sea surrounded by seven densely populated big cities in Türkiye and impacted by various anthropogenic activities, has experienced more and more mucilage blooms in the last two decades. The factors include discharge of domestic wastewater, excessive industrialization, agricultural runoff, commercial fishing, shipbuilding, specialized marine terminals with excessive maritime traffic. In spring 2021, a massive mucilage bloom impacted the whole marine ecosystem, leading to major governmental and public monitoring and mitigation efforts (Yibar et al. 2025).

The influx of untreated sewage, industrial pollutants, and the release of agricultural fertilizers into the water exacerbates the situation. These blooms not only affect water quality and fish populations but also pose risks to public health and tourism. This significant environmental concern is primarily driven by eutrophication and pollution from land-based sources, including untreated wastewater and agricultural runoff. These factors lead to nutrient overenrichment, particularly N and P, which support the rapid growth of phytoplankton and other microorganisms. When these organisms die, they decompose, contributing to the accumulation of organic matter that forms mucilage. This gelatinous substance disrupts marine life by depleting oxygen levels, blocking sunlight, and smothering aquatic habitats, thereby harming biodiversity (Yildirim et al. 2022). Addressing the mucilage problem requires better wastewater treatment, stricter pollution control, and effective nutrient management strategies (Bilgili et al. 2022; Yilmaz et al. 2024).

The excessive accumulation of fertilizers in soil poses significant risks to both the environment and human health, primarily a consequence of surface runoff into the marine environment and leaching into groundwater. To address these challenges, cost-effective, eco-friendly wastewater treatment technologies that maximize resource recovery are urgently needed (Lan Chi et al. 2023). One promising approach is the use of microalgae for removing pollutants, such as heavy metals and nutrients, from wastewater (Plöhn et al. 2021). This method offers advantages over conventional physicochemical techniques due to its higher nutrient removal efficiency and phytoremediation potential (M'Arimi et al. 2020). By assimilating N and P into their biomass, microalgae provide an eco-friendly and sustainable solution for nutrient removal in wastewater systems with high nutrient loads (Śniatała et al. 2024).

Microalgae produce colors, proteins, lipids, carbohydrates, vitamins, and antioxidants inexpensively. It also describes the mechanism and influencing factors by which microalgae remove nutrients and pollutants from wastewater and examines their purification effectiveness on wastewater from diverse sources (Liu and Hong 2021). Algae may utilize wastewater nutrients to generate other beneficial products, according to Goh et al. (2019). Phytoremediation uses microalgae to remove pollutants, including xenobiotics and nutrients, from wastewater before discharge or reuse (Goh et al. 2019). According to de Paula Pereira et al. (2024), recovering nutrients from wastewater via the use of microalgae for wastewater treatment in combination with biomass recovery for biofertilizer synthesis is a promising approach for sustainable agriculture.

As environmental awareness grows and regulatory pressures mandate sustainable waste management, the development of cost-effective alternatives has become essential. Microbial biomass has emerged as a viable option, aligning with circular economy principles by transforming waste into resources. Using bio-based fertilizers derived from microbial biomass not only supports sustainable wastewater treatment but also aligns with the European Commission's goal to reduce the use of non-renewable resources in fertilizer production by 30% (Namli et al. 2024).

As previously noted, microalgae biomass cultivated in wastewater offers a suitable and eco-friendly alternative to traditional inorganic fertilizers, supporting the principles of a circular economy (Álvarez-González et al. 2023). Related to that, Sharma et al. (2021) demonstrated that *Chlorella* biomass derived from wastewater treatment significantly enhanced the yields of spinach and baby corn when used as a biofertilizer. Similarly, previous studies have highlighted the beneficial effects of microalgae-based fertilization on plant growth and cultivation (Ronga et al. 2019). However, research on the agricultural applications of microalgae biomass specifically cultivated in wastewater is limited (Kang et al. 2021).

Wheat (*Triticum aestivum* L.), one of the most important crops globally, is a strategic cereal due to its ease of cultivation, high nutritional value, and adaptability to diverse dietary habits and environments (Khalid et al. 2023). This study introduces a dual-purpose approach using *Chlorella vulgaris* to remove N and P from wastewater while

repurposing the biomass as a biofertilizer for wheat cultivation. It uniquely addresses mucilage formation in the Istanbul Bosphorus and integrates wastewater treatment with sustainable agriculture. Additionally, it highlights the risk of heavy metal accumulation in soils, emphasizing the need for pre-treatment. By combining environmental remediation with soil fertility improvement, the study offers a scalable solution for both pollution control and sustainable farming. We hypothesize that utilizing microalgae for N and P removal from wastewater can mitigate eutrophication in marine ecosystems, while the resulting biomass could serve as a sustainable fertilizer, improving soil fertility and supporting wheat production.

Within the scope of this study, it was aimed to assess (1) the reduction of N and P in the discharge water of Advanced Biological WWTPs using microalgae (*Chlorella vulgaris*) and (2) the impact of the resulting biomass on wheat cultivation. The primary objective was not only to retain the nutrients responsible for mucilage formation in Istanbul Bosphorus but also to repurpose the microalgae biomass obtained through phytoremediation as a biofertilizer for wheat cultivation. This research contributes to mitigate mucilage in seawater while exploring the feasibility of using microalgae biomass as a sustainable agricultural input, paving the way for potential large-scale applications.

2 Materials and methods

2.1 Wastewater Collection

Wastewater samples were collected from Ambarlı (641421.78 E, 4539038.43 N) and Pasakoy (691810.19 E, 4542118.86 N) Advanced Biological WWTPs, in Istanbul, Türkiye. Both plants primarily treat domestic wastewater. Daily average treatment capacities of the plants are 4×10^5 m^3, and 2×10^5 m^3, respectively. After sampling, they were transported under controlled conditions to the Laboratory, Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Ankara, Türkiye for further analysis and experimentation and stored at 4 ºC. The schematic representation of the experimental workflow was illustrated in Fig. 1.

2.2 Physicochemical Characterization of Wastewaters

The physicochemical parameters of samples were analyzed using standard methods, including pH and electrical conductivity (EC) measurements (Richards 1954). Cations (iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg) and heavy metals (cadmium (Cd), chromium (Cr), (nickel) Ni, and lead (Pb) were quantified using an Inductively Coupled

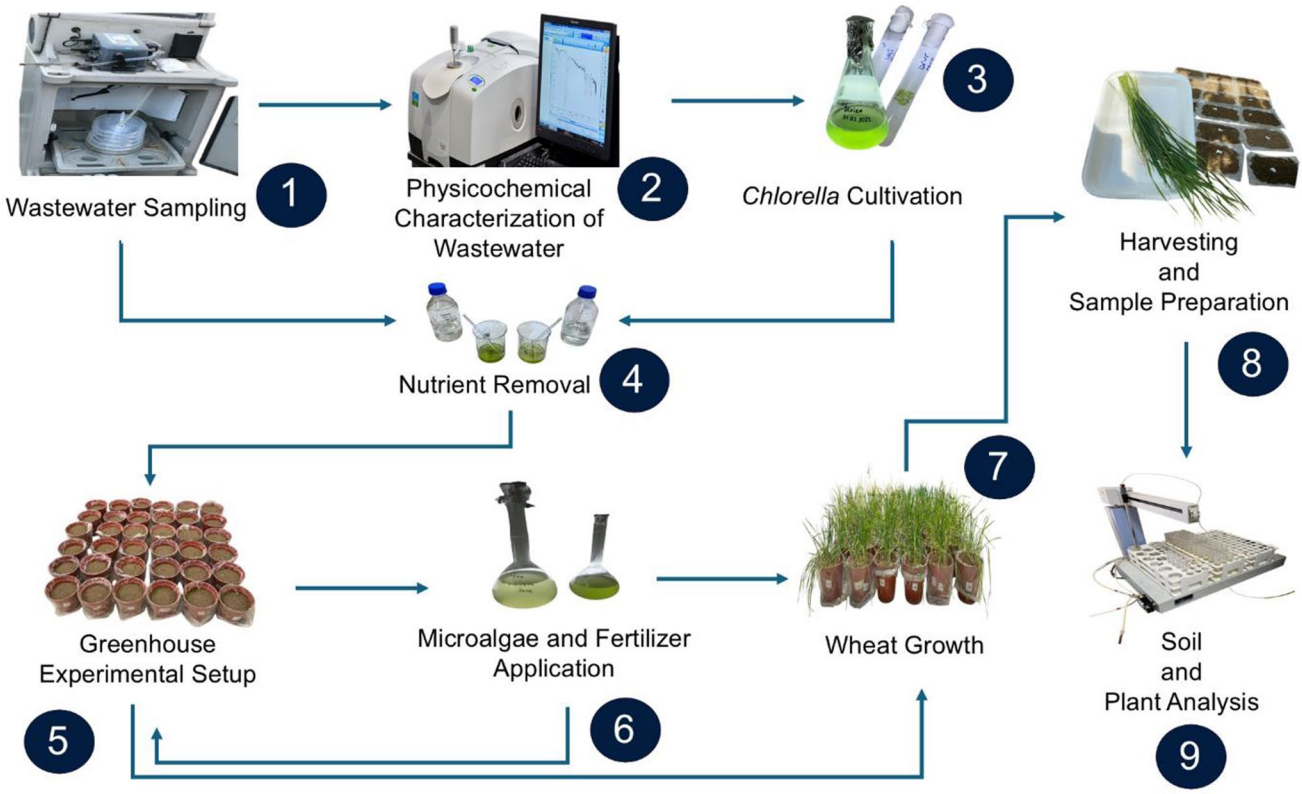


Fig. 1 Schematic representation of the experimental workflow

Plasma Optical Emission spectroscopy (ICP-OES) (Perkin Elmer Optima 2100 DV, Waltham, MA, USA). To ensure reproducibility, all analyses were performed in triplicate under controlled laboratory conditions.

2.3 *Chlorella vulgaris* Strain and Growth Conditions

Chlorella vulgaris (strain: *Chlorella vulgaris*) was supplied by UTEX 2714 (the Culture Collection of Algae at the University of Texas at Austin, USA) and maintained on protease medium (Pr) with continuous light irradiation (a mix of warm-white and cool-white fluorescent lamps) at 3200 lx in a 250 ml Erlenmeyer flask. The temperature was controlled at 20 ± 1 °C, and periodicity was 12/12 h L/D. *Chlorella vulgaris* was cultivated in BG-11 medium with an initial pH of about 7.0 at 25 ± 1 °C and fluorescent light of 25 µmol photons/m^2. The light cycle consisted of 16 h of light and 8 h of darkness. *Chlorella vulgaris* filaments in the plates were transferred to BG11 media with the help of a Pasteur pipette under sterile conditions and multiplied under the same conditions (Gao et al. 2020; Hong et al. 2012).

2.4 Nutrient Removal

The nutrient removal capacity (NRC) of *Chlorella vulgaris* in the sampled wastewater was determined by preparing *Chlorella vulgaris* suspension which was inoculated into 10 ml flasks for each wastewater sample. Total nitrogen (TN) and total phosphorus (TP) contents in the treated wastewater were analyzed at 30 min and 5 h after inoculation of the algal cell for nutrient reduction. The NRC was calculated using the following equation (Salgueiro et al. 2024):

$$NRC = \frac{(\mathrm{IC}\ (\mathrm{mg\,L-1}) - \mathrm{FC}\ (\mathrm{mg\,L-1}))\ ^{*}100}{\mathrm{IC}\ (mg\ L-1)} \quad (1)$$

where IC is the initial concentration and FC is the final concentration of nutrients.

2.5 Greenhouse Experiment

A greenhouse experiment was conducted in the Ankara University Faculty of Agriculture, Department of Soil Science and Plant Nutrition (39°57 × 44′′ N, 32°51 × 46′′ E, and an altitude of 849 m) from April to May 2022. The soil used in the experiment was sampled from 0 to 30 cm depth. The experiment, conducted in a completely randomized design to investigate the effects of microalgae (*Chlorella vulgaris*) on wheat cultivation, included triplicate treatments and controls, with pots rotated weekly to minimize greenhouse environmental gradient effects. Hereby, it was applied two different doses (0.01 and 0.04 g kg^{-1}) of *Chlorella vulgaris* to the soil with and without DAP fertilizer (CF: 150 kg ha^{-1}) in combination with the same doses of microalgae.

Wheat plants (*Triticum aestivum* L. cv. Bezostaja-1) were grown in plastic pots (16 cm length, 17.5 cm top, and 12.0 cm bottom diameter) filled with 2 kg of air-dried soil mixed with microalgae and fertilizer. The soil was moistened with deionized (DI) water before sowing 20 seeds at a 6 cm depth. After seven days, germination was recorded, and seedlings were thinned to 10 per pot. A further 50 mg kg^{-1} N (as NH_4NO_3) was added on the 30th day after sowing. The wheat plants were harvested from the base closest to the soil at the end of a 10-week vegetation period, during which no pesticides were used. Harvested plants were washed, dried at 65 °C, weighed, and ground (200 µm sieve) for analysis.

2.6 Analysis of Soil and Plant Samples

The terms Ambarlı and Pasakoy Station refer to soil and plant analysis results from after the greenhouse experiment. After wheat plants were harvested, the soil from each pot was collected, air-dried, ground, and sieved through a 2-mm mesh for laboratory analysis. The samples were then analyzed for pH, EC, soil organic matter (SOM), TN, available P, exchangeable K, total Ni, and total Pb. pH and EC were determined in a 1:2.5 soil: water ratio (w/v) as proposed by Jackson (1952). Soil organic matter was analyzed by the modified Walkley-Black method Nelson (1996). Total N was analyzed by the Kjeldahl method Bremner (1965) and available P was measured according to the procedure proposed by Olsen (1954). For the estimation of exchangeable K, extraction was carried out in ammonium acetate, and concentration was measured using a flame photometer (Prasad 2006). Total Ni and total Pb in acid digestion by ICP-OES instrument.

The plant samples were digested with a 4:1 acid mixture (HNO_3-$HClO_4$ 65 and 60% pure, Merck, respectively) (Kalra 1998). Total N in the plant samples was determined by the Kjeldahl method. Total P and K concentrations were determined by ICP-OES. Total Ca, Mg, Na, Fe, Zn, Cu, Mn, Ni, and Pb concentrations were analyzed by ICP-OES. All analyses were performed in triplicate. The peach leaves received from the National Institute of Standards and Technology were used as standard reference material with code 1547. Plant nutrient content is calculated as a function of their concentrations and respective dry weights.

2.7 Statistical Analysis

The greenhouse experiment was set up in a completely randomized design and each treatment contained three replicate pots. Analysis of variance (ANOVA) was performed

Table 1 Some physicochemical properties of the used wastewater

Parameters	WWTPs	
	Ambarlı	Pasakoy
pH	8.08	7.95
EC, µS cm^{-1}	978	1382
Color	Greyish	Greyish
Odor	Odorous	Odorous
P, mg L^{-1}	1173	0.088
Fe, mg L^{-1}	0.119	0.072
Cu, mg L^{-1}	0.005	0.005
Zn, mg L^{-1}	0.021	0.068
Mn, mg L^{-1}	0.188	0.27
Na, mg L^{-1}	76.11	139.90
Ca, mg L^{-1}	32.68	31.84
K, mg L^{-1}	15.33	19.17
Mg, mg L^{-1}	8.29	7.72
Cd, mg L^{-1}	0.001	0.001
Cr, mg L^{-1}	0.006	0.007
Ni, mg L^{-1}	0.047	0.047
Pb, mg L^{-1}	0.007	0.006

WWTPs: Wastewater treatment plants; EC: Electrical conductivity

Table 2 Some physical and chemical properties of the experimental soil

Properties (Method)	Experimental Soil
Texture (Bouyoucos)	SiCL
$CaCO_3$ (Scheibler), %	7.41
pH (1:2.5 water)	7.88
EC (1:2.5 water), dS m^{-1}	0.38
Soil organic matter (Walkley-Black), %	0.15
P ($NaHCO_3$-extractable), mg kg^{-1}	1.55
Total-N (Kjeldahl), %	0.06
K (NH_4OAc-extractable), mg kg^{-1}	178.40
Ca (NH_4OAc-extractable) %	0.49
Mg (NH_4OAc-extractable), %	0.05
Na (NH_4OAc-extractable), %	0.009
Zn (DTPA-extractable), mg kg^{-1}	0.54
Fe (DTPA-extractable), mg kg^{-1}	4.39
Cu (DTPA-extractable), mg kg^{-1}	1.75
Mn (DTPA-extractable), mg kg^{-1}	3.09
Total Ni, (acid digestion), mg kg^{-1}	45.25
Total Pb, (acid digestion), mg kg^{-1}	7.23

EC: Electrical conductivity

on the data using OriginPro software, and the significant differences between the treatment groups were calculated by Tukey's multiple range test ($p<0.05$). Figures were generated using OriginPro software (version 2021). R Studio software (Version 2023.03.0+386, https://www.r-project.org/) was used for principal component analysis (PCA) on the correlation matrix of treatments and variables. The responses of all the traits under each treatment were combined and used as index values for PCA analysis. PCA employed index values from all attributes under each treatment. These index values determined response variable vector correlation and ordination space comparisons. Two-way heatmap clustering analysis (HCA) was done on the same dataset as PCA. The dissimilarity matrix was calculated using the 'euclidean procedure' and Pearson correlation. R's 'prcomp' function in the 'factoextra' package developed PCA and HCA (Kassambara and Mundt 2020). Heatmap function in R's 'pheatmap' package hierarchically grouped data (Kolde 2019).

3 Results

3.1 Wastewater Characterization

The main physicochemical wastewater characteristics were presented in Table 1, 2 and evaluated with Water Pollution Control Regulation (Türkiye), European Union Water Framework Directive and Urban Wastewater Treatment Directive (91/271/EEC), Irrigation Water Standards, Food and Agriculture Organization (FAO), and Water Pollution Control Regulation, and World Health Organization (WHO) – Wastewater Guidelines for Irrigation. Both samples exhibited pH values suitable for standard wastewater treatment processes but were on the upper range of neutrality. Both wastewater samples exhibited pH values suitable for standard wastewater treatment processes but were on the upper range of neutrality, with Ambarlı at 8.08 and Pasakoy at 7.95. Pasakoy wastewater has a higher salinity potential, likely due to a higher ionic load, particularly Na content of 139.90 mg L^{-1}, compared to 76.11 mg L^{-1} in Ambarlı. This could influence its suitability for reuse in irrigation without further treatment. Both wastewaters are greyish in color and odorous, which is typical of domestic wastewater containing organic contaminants. A significant difference was observed in P concentrations. The P level in Ambarlı (1173 mg L^{-1}) is extremely elevated and could pose a severe eutrophication risk to receiving water bodies. In contrast, Pasakoy has a P concentration of 0.088 mg L^{-1}, which is more typical of treated or diluted wastewater. Heavy metal concentrations, including Cd, Cr, Ni, and Pb, were generally low and similar between the two samples. Both Ambarlı and Pasakoy wastewaters have acceptable N levels for discharge under most regulatory frameworks. However, for reuse or discharge into sensitive ecosystems, continuous monitoring and, if necessary, additional treatment to further reduce N levels may be required. These observations suggest that while both wastewaters share similarities in general water quality parameters, the exceptionally high P levels in Ambarlı and the higher salinity of Pasakoy may necessitate tailored treatment strategies depending on the intended disposal or reuse scenarios.

3.2 Soil Description

The experimental soil is classified as SiCL (Silty clay loam) (Soil Survey Staff 1999). The main physical and chemical soil characteristics were as follows; equivalent calcium carbonate content of 7.41%, a pH of 7.88 (1:2.5 soil/water), an EC of 0.38 dS m^{-1} (1:2.5 soil/water), 0.15% SOM, 1.55 mg kg^{-1} available P, and 0.06% total N. According to these results, the soil used in the experiment was a slightly alkaline and calcareous soil with low SOM but a sufficient amount of total N and available P.

3.3 Phytoremediation Efficiency of *Chlorella vulgaris* in Different Wastewater Samples

Analysis of TN and TP contents performed to determine the efficiency of *Chlorella vulgaris* in influencing phytoremediation processes in different wastewater samples. Figure 2 shows the TN and TP removal by *Chlorella vulgaris* in treating respective water samples. The effect of *Chlorella vulgaris* on TN removal in two wastewater samples was statistically significant ($p<0.05$). In both wastewater samples, *Chlorella vulgaris* recorded the highest TN reduction in the first 30 min, at 43.65% and 17.63%, respectively (Fig. 2A and B). The effect of *Chlorella vulgaris* on TP removal in two wastewater samples was found statistically significant ($p<0.05$) similar to TN removal. While TP removal followed a pattern similar to TN, their removal efficiencies varied with experiment time. The maximum TP removal rates reached 75.42% and 19.16%, at 300 min. No minimum TP removal was observed at any point during the experiment (Fig. 2C and D). This suggests that microalgae growth after 30 min resulted in low protein content.

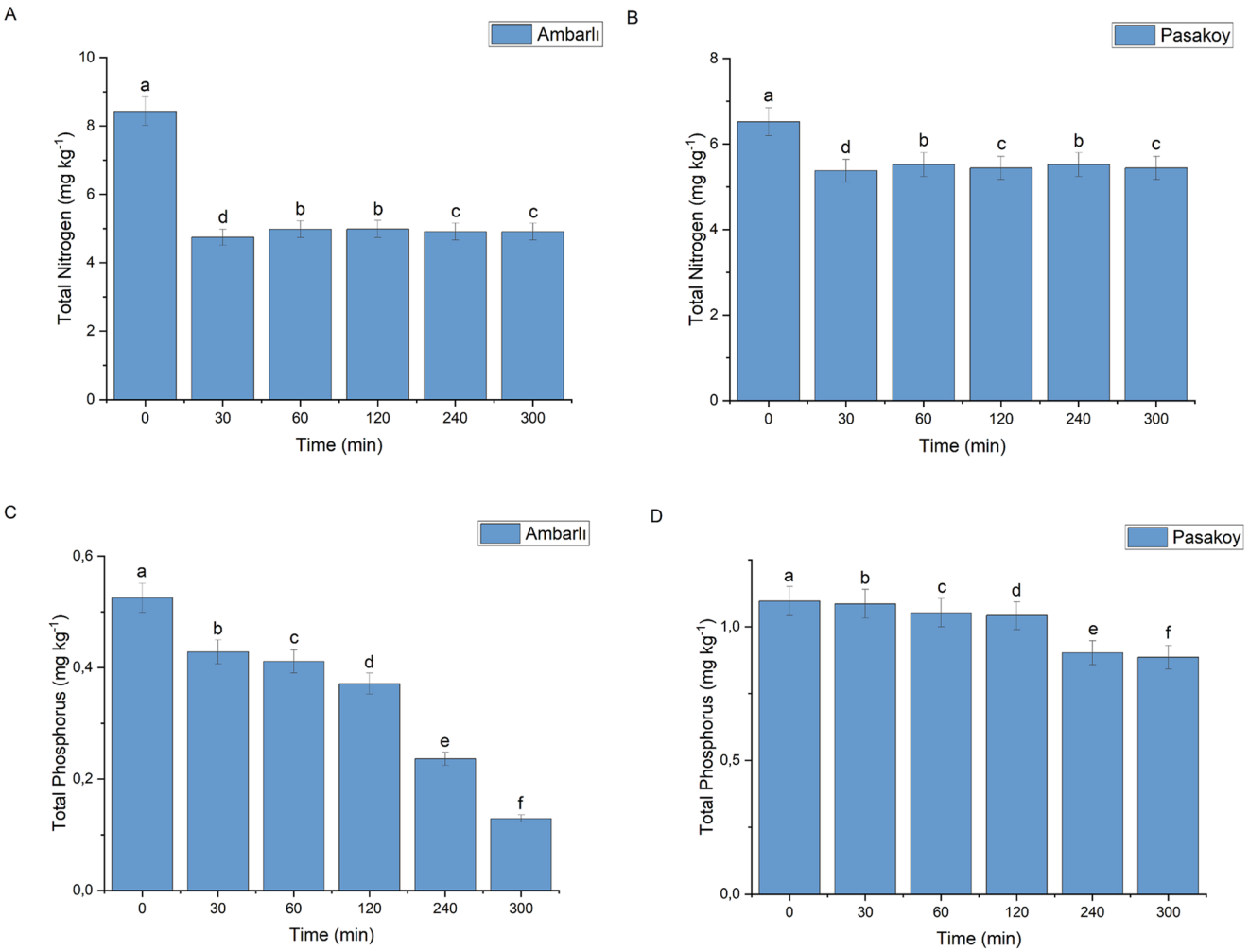


Fig. 2 Removal of Total Nitrogen (TN) in Ambarlı (**A**) and Pasakoy (**B**). Removal of Total Phosphorus (TP) in Ambarlı (**C**) and Pasakoy (**D**). Different letters (a, b, c, d, e, and f) indicate significant differences between the time and total removal of TN and TP in the respective wastewaters ($n=3$) at $p<0.05$ level based on Tukey's multiple range test. The values are the means of 3 replicates ± SE

3.4 Greenhouse Experiment

3.4.1 Soil Analysis Results after Harvesting the Wheat Plant

To determine the effect of *Chlorella vulgaris* removing N and P from wastewater from Ambarlı and Pasakoy Stations on wheat plant growth and some soil properties, greenhouse experiments were carried out by growing wheat plants separately for each wastewater plant under controlled conditions, and soil analysis results are given below. Figures 3 and 4 show the soil analysis results of a greenhouse experiment conducted by growing wheat plants under controlled conditions to reveal the effect of *Chlorella vulgaris* after the phytoremediation processes in Ambarlı and Pasakoy WWTPs.

The pH value of the soil treated with microalgae from Ambarlı wastewater showed a statistically significant increase (Fig. 3); however, no statistically significant changes in pH were observed in the soil treated with microalgae from Pasakoy wastewater compared to the control ($p<0.05$). EC was found higher in the control soil compared to CF alone in all soils ($p<0.05$). The highest SOM value was found only in the CF treatment and in the CF co-application with both low and high doses of algal digestates, with these values being higher than those of algal digestates alone ($p<0.05$) (Figs. 3 and 4). In soils treated with microalgae from Ambarlı wastewater where algae was co-applied with CF, N content was higher than that of algae alone ($p<0.05$), while in soils treated with microalgae from Pasakoy wastewater, N values were the same regardless of the dose. In both soils, microalgae applications increased total N compared to the control (Figs. 3 and 4). The highest available P value was found in the soils treated with CF with high doses of microalgae treated with Ambarlı wastewater ($p<0.05$), while no statistical significance was found in soils treated with microalgae from Pasakoy wastewater depending on the treatments ($p>0.05$). Using *Chlorella vulgaris* alone increased available K content more than CF alone in all soils ($p<0.05$) (Figs. 3 and 4). The highest available Ni values were found in CF and CF co-application with low and high doses of *Chlorella vulgaris*, and these values were higher than the control for Ambarlı ($p<0.05$). The highest available Ni values were found only in CF and CF co-application with low and high doses of *Chlorella vulgaris*, and these values were higher than those of *Chlorella vulgaris* application alone for Pasakoy ($p<0.05$). Although there was an increase in the amount of Ni due to microalgae applications in both experiments, this increase was not at the level of point-source pollution. In both experiments, an increase was observed in available Pb amounts due to microalgae applications ($p<0.05$).

3.4.2 The Effects of Microalgae on the Yield Components and Macro Elemental Composition of the Wheat Plant

The effects of treatments on plants' fresh weight (A), dry weight (B), plant total N (C), plant P (D), plant K (E), plant total Ca (F), plant Mg (G), and plant Na (H) were found to be significant ($p<0.05$) as seen in Figs. 5 and 6. The

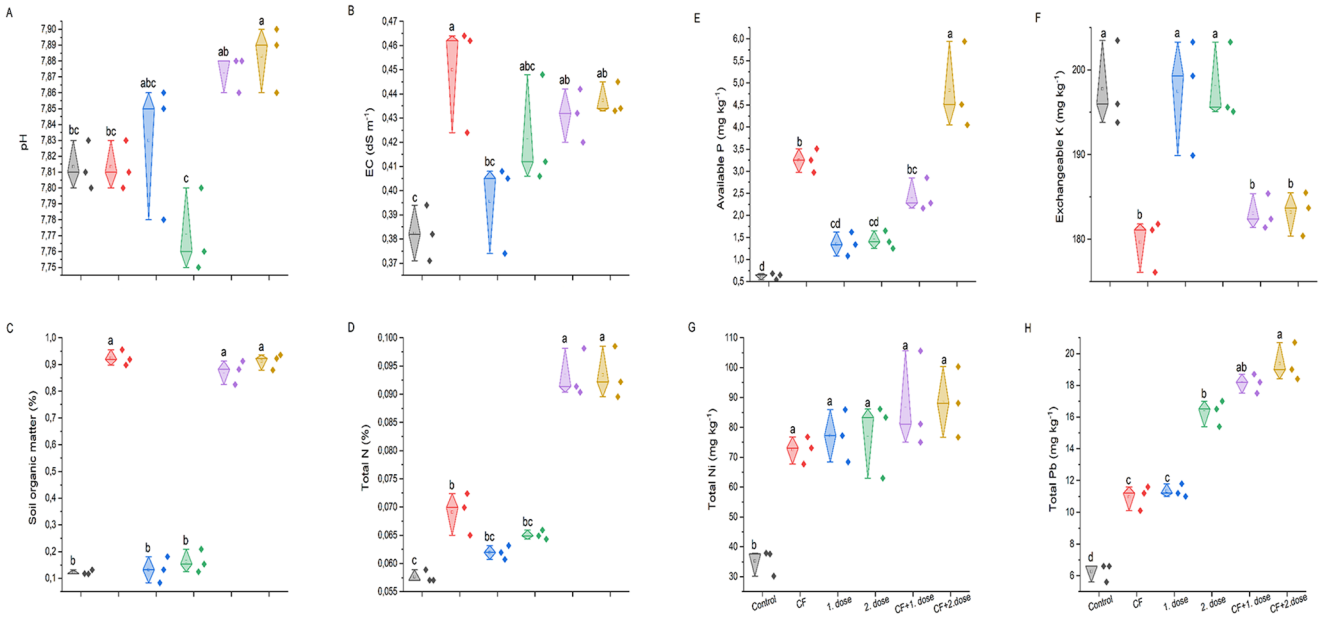


Fig. 3 Assessing the impact of *Chlorella vulgaris* after phytoremediation at Ambarlı Wastewater Treatment Plant (WWTP). pH (**A**), EC (**B**), SOM (**C**), Total N (**D**), Available **P** (**E**), Exchangeable K (**F**), Total Ni (**G**), and Total Pb (H). The values are the means of 3 replicates ± SE. Different letters in each diamond column represent significant differences at $p<0.05$ level based on Tukey's multiple range test. CF: Chemical Fertilization (150 kg ha^{-1} Diammonium Phosphate), 1st Dose: 0.01 g kg^{-1}, 2nd Dose: 0.04 g kg^{-1}

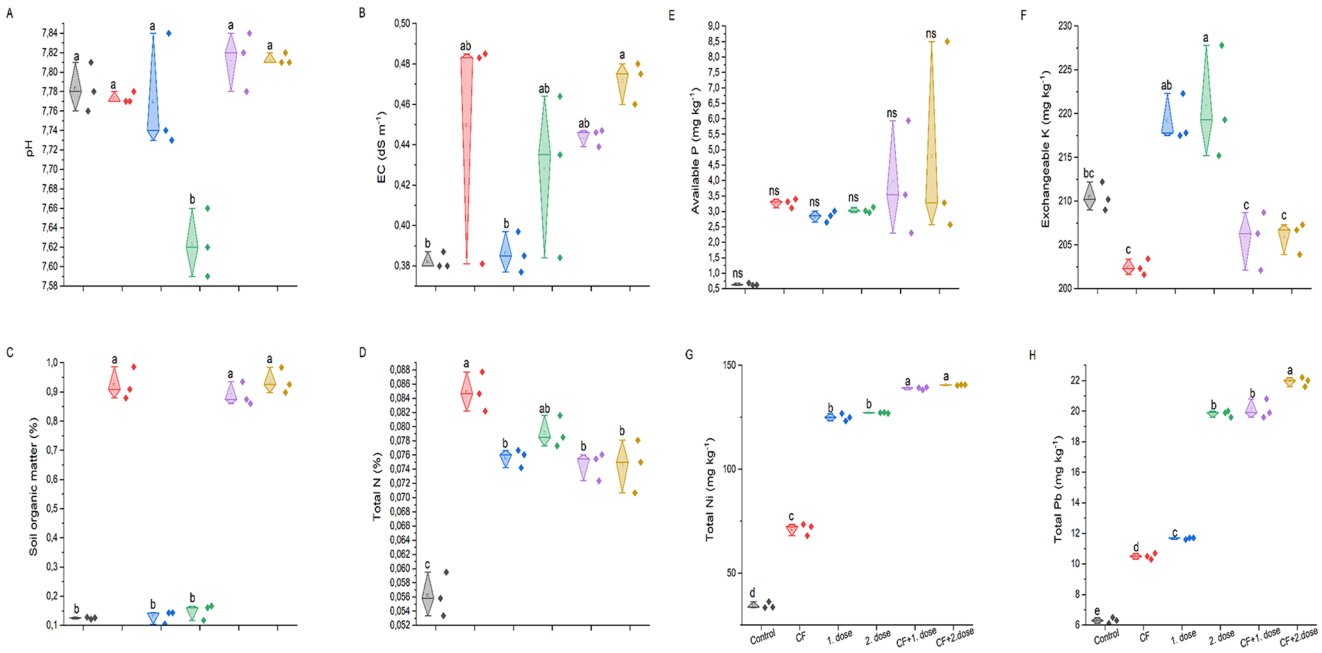


Fig. 4 Assessing the impact of *Chlorella vulgaris* after phytoremediation at Pasakoy Wastewater Treatment Plant (WWTP). pH (**A**), EC (**B**), SOM (**C**), Total N (**D**), Available P (**E**), Exchangeable K (**F**), Total Ni (**G**), and Total Pb (**H**). The values are the means of 3 replicates ± SE. Different letters in each diamond column represent significant differences at $p < 0.05$ level based on Tukey's multiple range test. CF: Chemical Fertilization (150 kg ha^{-1} Diammonium Phosphate), 1st Dose: 0.01 g kg^{-1}, 2nd Dose: 0.04 g kg^{-1}, ns: not significant

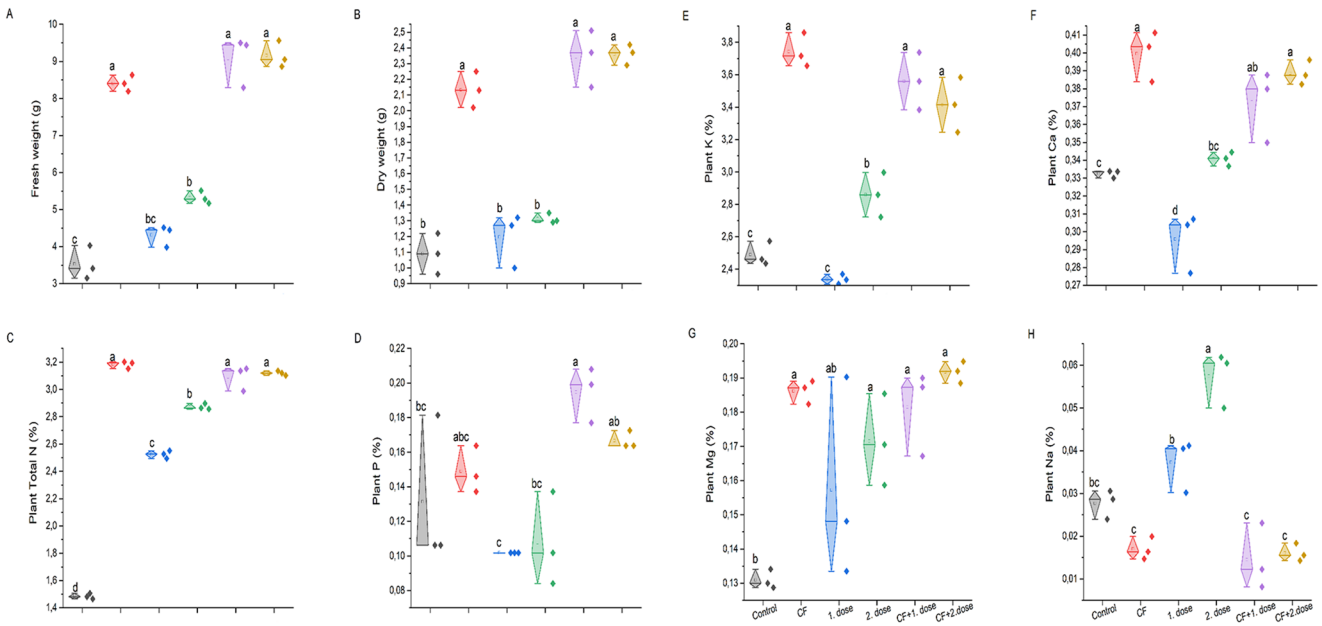


Fig. 5 The yield components and macroelemental composition of the wheat plant for Ambarlı Station. Fresh weight (**A**), Dry weight (**B**), Plant Total N (**C**), Plant P (**D**), Plant K (**E**), plant total Ca (**F**), Plant Mg (**G**), and Plant Na (**H**). The values are the means of 3 replicates ± SE. Different letters in each diamond column represent significant differences at $p < 0.05$ level based on Tukey's multiple range test. CF: Chemical Fertilization (150 kg ha^{-1} Diammonium Phosphate), 1st Dose: 0.01 g kg^{-1}, 2nd Dose: 0.04 g kg^{-1}

present study demonstrated that the application of *Chlorella vulgaris* treatments can enhance wheat growth parameters (fresh and dry weight), nutrient uptake, and the nutritional status (N, P, K, Ca, Mg, and Na) in wheat plants. In both experiments, wheat's fresh and dry weight increased significantly after the microalgae and CF treatment ($p < 0.05$). For Ambarlı wastewaters, the highest fresh and dry biomass weights were measured as 9.15 ± 0.36 g and 2.36 ± 0.06 g,

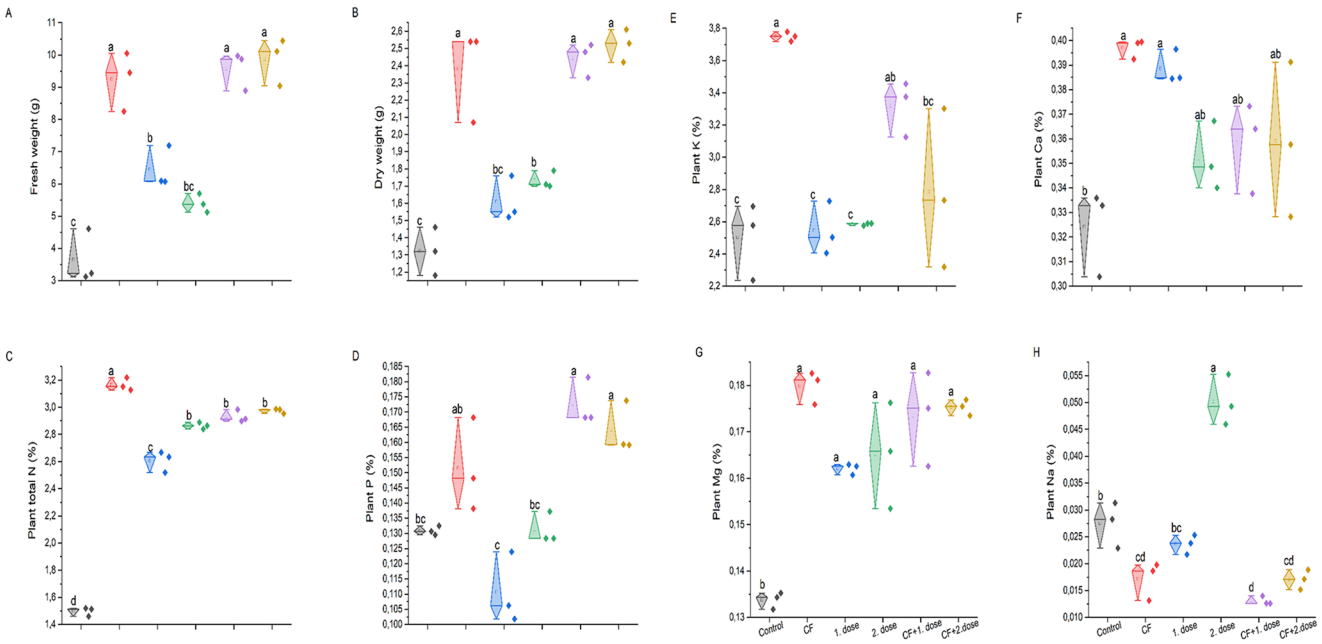


Fig. 6 The yield components and macroelemental composition of the wheat plant for Pasakoy Station. Fresh weight (**A**), Dry weight (**B**), Plant Total N (**C**), Plant P (**D**), Plant K (**E**), Plant Ca (**F**), Plant Mg (**G**), and Plant Na (**H**). The values are the means of 3 replicates ± SE. Different letters in each diamond column represent significant differences at $p < 0.05$ level based on Tukey's multiple range test. CF: Chemical Fertilization (150 kg ha^{-1} Diammonium Phosphate), 1st Dose: 0.01 g kg^{-1}, 2nd Dose: 0.04 g kg^{-1}

respectively, when applying CF + 2nd dose treatment; for Pasakoy, the highest fresh and dry biomass weights were measured as 9.86 ± 0.73 g and 2.52 ± 0.06 g, respectively, when applying CF + 2nd dose treatment (Figs. 5A, B and 6A, 6B). The highest N content of wheat plants was determined in the CF + 2nd dose (3.11 ± 0.01) treatment in Ambarlı Station, while the lowest plant N value was found in the control (1.48 ± 0.02) ($p < 0.05$) (Fig. 5C). However, the highest N contents of wheat plants were determined in CF alone (3.16 ± 0.02) treatment in Pasakoy Station, while the lowest plant N values were found in the control ($p < 0.05$) (Fig. 6C). The P contents of the wheat plants were higher in all treatments compared to the control. Significantly higher values of available P of 0.19 ± 0.009, and 0.17 ± 0.004 were observed in CF + 1st dose in Ambarlı and Pasakoy, respectively. Using CF + 1st dose led to an increase of 46.15% and 30.76% in the available P in soils, respectively (Figs. 5D and 6D). In both experiments, applying microalgae together with CF increased the amount of K in wheat plants compared to the control group ($p < 0.05$). A significantly higher amount of K was found at 3.74 ± 0.06%, and 3.74 ± 0.01% in CF in Ambarlı and Pasakoy, respectively (Figs. 5E and 6E). For Ambarlı, the lowest Ca content in plants was observed in the first dose treatment (0.29 ± 0.009%), while the highest was in the CF treatment (0.33 ± 0.001%). For Pasakoy, the lowest Ca content was found in the 1st dose treatment (0.39 ± 0.002%), and the highest was in the CF treatment (0.32 ± 0.01%) (Fig. 6F). In both experiments, *Chlorella vulgaris* treatments significantly increased Mg concentration, with higher Mg levels observed in treatments, where microalgae were applied together with CF compared to microalgae alone (Figs. 5G and 6G). For Ambarlı, the highest Na content in plants was 0.05 ± 0.003% in the 2nd dose treatment, while the lowest was 0.01 ± 0.002% in the CF application. For Pasakoy, the highest Na content was 0.05 ± 0.004% in the 2nd dose treatment, and the lowest was 0.01 ± 0.008% in the CF + 1st dose treatment (Figs. 5H and 6H).

3.4.3 The Effects of Microalgae on the Microelement and Heavy Metal Compositions of the Wheat Plant

The effects of treatments on plants' total Fe (A), Zn (B), Cu (C), Mn (D), Ni (E), Pb (F) were found to be significant ($p < 0.05$) as seen in Figs. 7 and 8. Figures 7A and 8A depict the treatment-induced changes in plant Fe as a function of *Chlorella vulgaris*. The findings indicate that changes in treatment had statistically significant effects on these variables ($p < 0.05$). For plant Fe, the highest mean concentration value was obtained for CF + 2nd dose (159.4 ± 4.80 mg kg^{-1}) and the lowest for 2nd dose (73.6 ± 2.41 mg kg^{-1}) for Ambarlı. In Pasakoy, the highest average concentration value was obtained for 1st dose (148.06 ± 5.76 mg kg^{-1}) and the lowest for 2nd dose (103.13 ± 2.25 mg kg^{-1}). However, fertilization of wheat with *Chlorella vulgaris* reduced plant Fe in soils compared to those fertilized by CF alone in

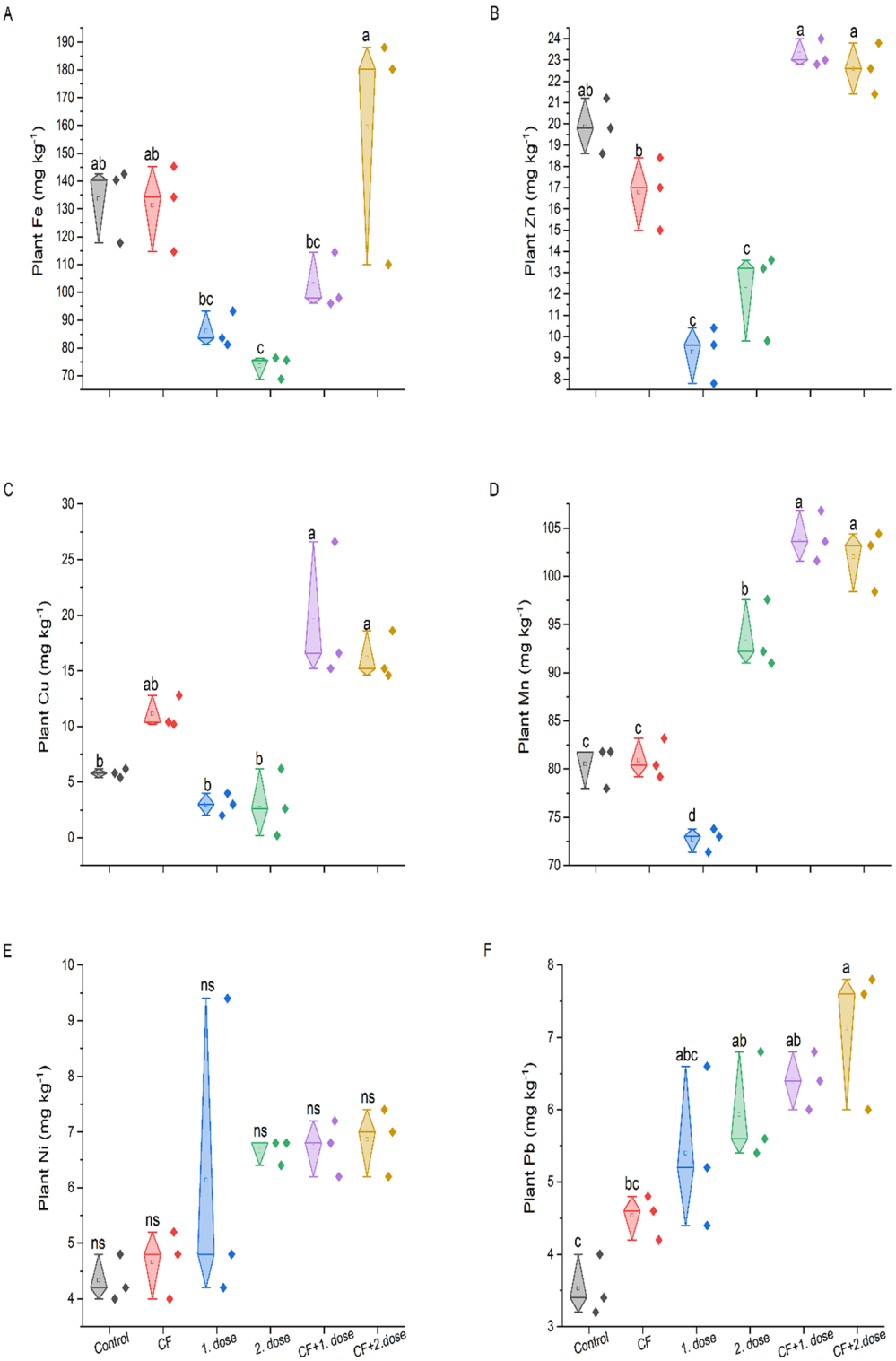


Fig. 7 The microelement and heavy metal contents of the plants for Ambarlı Station. Plant Fe (**A**), Plant Zn (**B**), Plant Cu (**C**), Plant Mn (**D**), Plant Ni (**E**), and Plant Pb (F). The values are the means of 3 replicates ± SE. Different letters in each diamond column represent significant differences at $p < 0.05$ level based on Tukey's multiple range test. CF: Chemical Fertilization (150 kg ha^{-1} Diammonium Phosphate), 1st Dose: 0.01 g kg^{-1}, 2nd Dose: 0.04 g kg^{-1}, ns: not significant

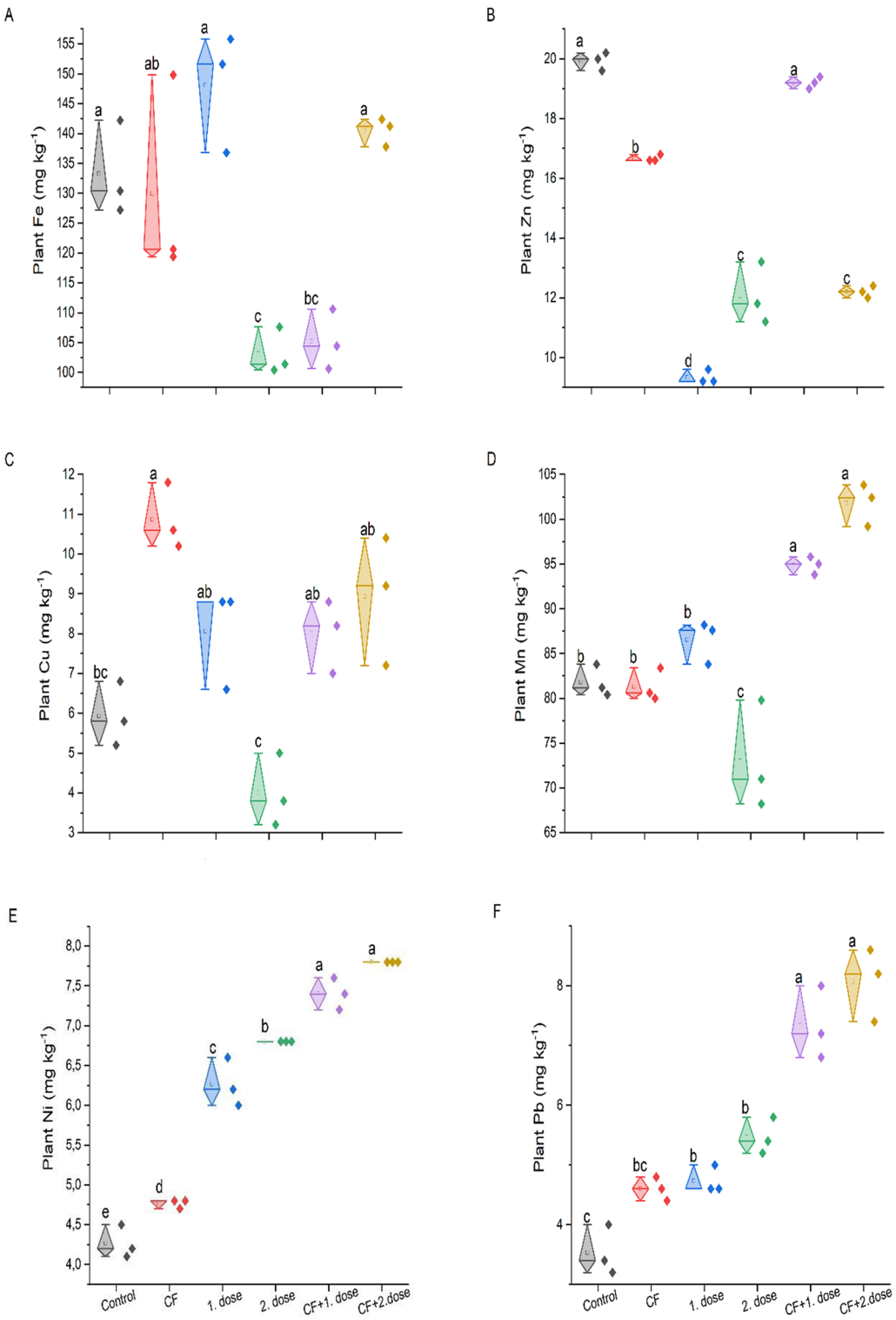


Fig. 8 The microelement and heavy metal contents of the plants for Pasakoy Station. Plant Fe (**A**), Plant Zn (**B**), Plant Cu (**C**), Plant Mn (**D**), Plant Ni (**E**), and Plant Pb (**F**). The values are the means of 3 replicates ± SE. Different letters in each diamond column represent significant differences at $p < 0.05$ level based on Tukey's multiple range test. CF: Chemical Fertilization (150 kg ha^{-1} Diammonium Phosphate), 1st Dose: 0.01 g kg^{-1}, 2nd Dose: 0.04 g kg^{-1}

Ambarlı Station. A similar result was observed at Pasakoy Station in the 2nd dose application.

The changes in plant Zn using *Chlorella vulgaris* were found to be statistically significant ($p<0.05$). Plant Zn content of 23.26±0.37 mg kg^{-1} was recorded in CF+1st dose, which was significantly higher than CF (16.8±0.98 mg kg^{-1}), 1st dose (9.26±0.76 mg kg^{-1}), and 2nd dose (12.20±1.20 mg kg^{-1}) in Ambarlı Station. Plant Zn's highest average concentration value was obtained for control (19.93±0.17 mg kg^{-1}) and the lowest for 2nd dose (9.33±0.13 mg kg^{-1}) in Pasakoy. The highest Cu value was found in plants that were applied CF+1st dose (19.46±3.58 mg kg^{-1}), while the lowest was found in 1st dose (3±0.5 mg kg^{-1}) in Ambarlı, but Plant Cu was higher in the CF (10.86±0.48 mg kg^{-1}) compared to 2nd dose (4±0.52 mg kg^{-1}) in Pasakoy ($p<0.05$) (Figs. 7C and 8C). The lowest plant Mn content was 72.73±0.70 mg kg^{-1} in the 1st dose treatment and the highest was 104±1.51 mg kg^{-1} in the 2nd dose+CF treatment in Ambarlı ($p<0.05$), but the lowest plant Mn content was 73±3.49 mg kg^{-1} in the 2nd dose and the highest was 101.8±1.36 mg kg^{-1} in the CF+2nd dose treatment in Pasakoy ($p<0.05$) (Figs. 7D and 8D). The Mn value of the plant was found to be higher in the treatments in which microalgae was applied together with CF than when microalgae was applied alone.

The Ni value of plants increased with the treatments, but these increases were not statistically significant in Ambarlı Station ($p>0.05$). However, the lowest Ni content was 4.26±0.12 mg kg^{-1} in the control, and the highest was 7.80 mg kg^{-1} in the CF+2nd dose treatment. The Ni contents of plants were found to be higher in the treatments in which microalgae were applied together with CF rather than alone (Figs. 7E and 8E). The highest Pb content was 7.13±0.56 mg kg^{-1} in the CF+2nd dose treatment, and the lowest was 3.53±0.24 mg kg^{-1} in the control treatment in Ambarlı Station ($p<0.05$). The same effect was found at Pasakoy Station. The highest Pb content of wheat was 8.06±0.35 mg kg^{-1} in the CF+2nd dose treatment, and the lowest was 3.53±0.24 mg kg^{-1} in the control treatment (Figs. 7F and 8F).

3.5 Relationships Between these Variables Depending on the Treatments for Each Station

PCA was performed to understand the relationships between these variables depending on the treatments for each station. For this purpose, the identified soil properties and plant parameters were used in this study (Figs. 3, 4, 5, 6, 7 and 8). The PCA exhibits that treatments and variables were associated with PC1 and PC2 (75%), of which PC1 was the major component (60%) in Ambarlı (Fig. 9A). The colors of the individual variables represent their quality of representation of the principal component, abbreviated as 'Cos2′. The CF+doses treatments result in pH, EC, SOM, soil total N, soil available P, soil total Ni, soil total Pb, plant fresh weight (PFW), plant dry weight (PDW), Plant N, Plant P, Plant K, Plant Ca, Plant Mg, Plant Fe, Plant Zn, Plant Cu, Plant Mn, Plant Ni, and Plant Pb on the left side of the first axis (PC1). In contrast, only dose treatments showed soil K and plant Na parameters (right side of the PC1) (Fig. 9B). In parallel, in this study, CF+dose treatments corresponded to all parameters except soil K and Plant Na. Indeed, Fig. 9B showed that CF+doses and only doses were separate from each other in Ambarlı. For Ambarlı, it was observed that the contribution of "CF+dose" treatments to SOM, PFW, and PDW parameters is high. In addition, these treatments not only increase macro- and micronutrients in soil and plants but also contribute to the increase of heavy metal contents.

The heat map derived from HCA showed that all the soil and growth parameters under *Chlorella vulgaris* treatments could be grouped into two major clusters (Fig. 9C). Plant Na and soil K parameters were grouped into a separate cluster (I) with higher values under dose treatments, followed by CF+dose treatments. These parameters often showed a decrease in the CF+dose treatments. According to PCA results, the "CF" and "CF+dose" parameters were grouped into a separate cluster (II). Cluster A indicated the CF and CF+dose treatments, respectively. "Control" and "Dose" treatments were located in cluster B (Fig. 9C).

The PCA exhibits that treatments and variables were associated with PC1 and PC2 (66.5%), of which PC1 was the major component (46% in Pasakoy station) (Fig. 10A). The colors of the individual variables represent their quality of representation of the principal component, abbreviated as 'Cos2′. The CF+doses treatments result in pH, EC, SOM soil total N, soil available P, soil total Ni, soil total Pb, PFW, PDW, Plant N, P, K, Ca, Mg, Fe, Zn, Cu, Mn, Ni, and Pb on the left side of the first axis (PC1). In contrast, only dose treatments showed soil K and plant Na parameters (right side of the PC1). The same trend was observed at Pasakoy station (Fig. 10B).

The heat map derived from two-way HCA showed that all the soil and growth parameters under *Chlorella vulgaris* treatments could be grouped into two major clusters (Fig. 10C). Plant Na and soil K parameters were grouped into a separate cluster (I) with higher values under dose treatments, followed by CF+dose treatments. These parameters often showed a decrease in the CF+dose treatments. According to PCA results, the "CF" and "CF+dose" parameters were grouped into a separate cluster (II). Cluster A indicated the CF and CF+dose treatments, respectively. "Control" and "Dose" treatments were located in cluster B (Fig. 10C).

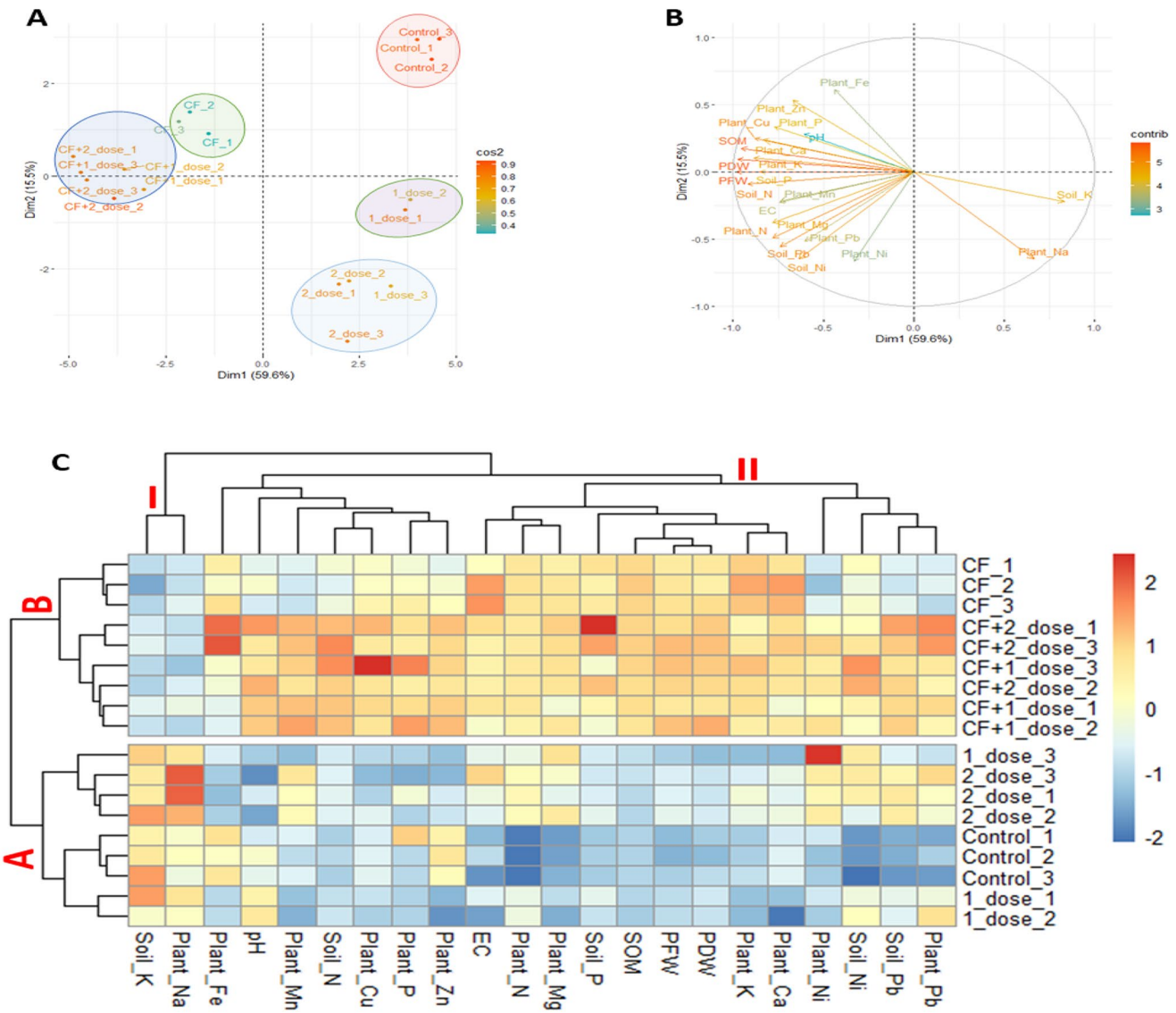


Fig. 9 (**A**) Principle component analysis (PCA) with Euclidian distance to control; (**B**) Principle component analysis (PCA) biplot based on treatments and parameters; and (**C**) Hierarchical clustering analysis (HCA) of treatments in Ambarlı station. Soil organic matter (SOM), plant fresh weight (PFW), and plant dry weight (PDW)

4 Discussion

N is an important and limiting nutrient for microalgae, being necessary for protein, nucleic acid, and chlorophyll molecule synthesis (Lourenco et al. 2002). Lower contents of N can lead to a significant reduction of chlorophyll production (da Silva Ferreira et al. 2017). Each microalgae species uses different transport and metabolic mechanisms to take in nutrients and convert them into components necessary for reproduction and growth (Beardall and Raven 2012). *Chlorella vulgaris*, for example, utilizes active transport mechanisms to uptake inorganic N (such as NO_3^- and NH_4^+), PO_4^{3-}, and CO_2 from its surrounding environment. These mechanisms enable *Chlorella vulgaris* to efficiently assimilate essential nutrients and use them in metabolic pathways that support cellular functions, photosynthesis, and biomass production. The species also employs mechanisms like carbon-concentrating mechanisms to optimize carbon fixation under varying environmental conditions (Ashour et al. 2024). The removal of N from wastewater is essential because of the potential damage it could cause to the ecosystem as a result of the eutrophication effect (Talib et al. 2023). The finding aligns with previous studies (Gour et al. 2016; Lu et al. 2023; Sisman-Aydin 2022).

P is a limiting nutrient for microalgae growth and development and plays a key role in several metabolic pathways, such as the Calvin cycle, phosphorylation processes and ATP synthesis (Chu et al. 2020). Thus, growth media with

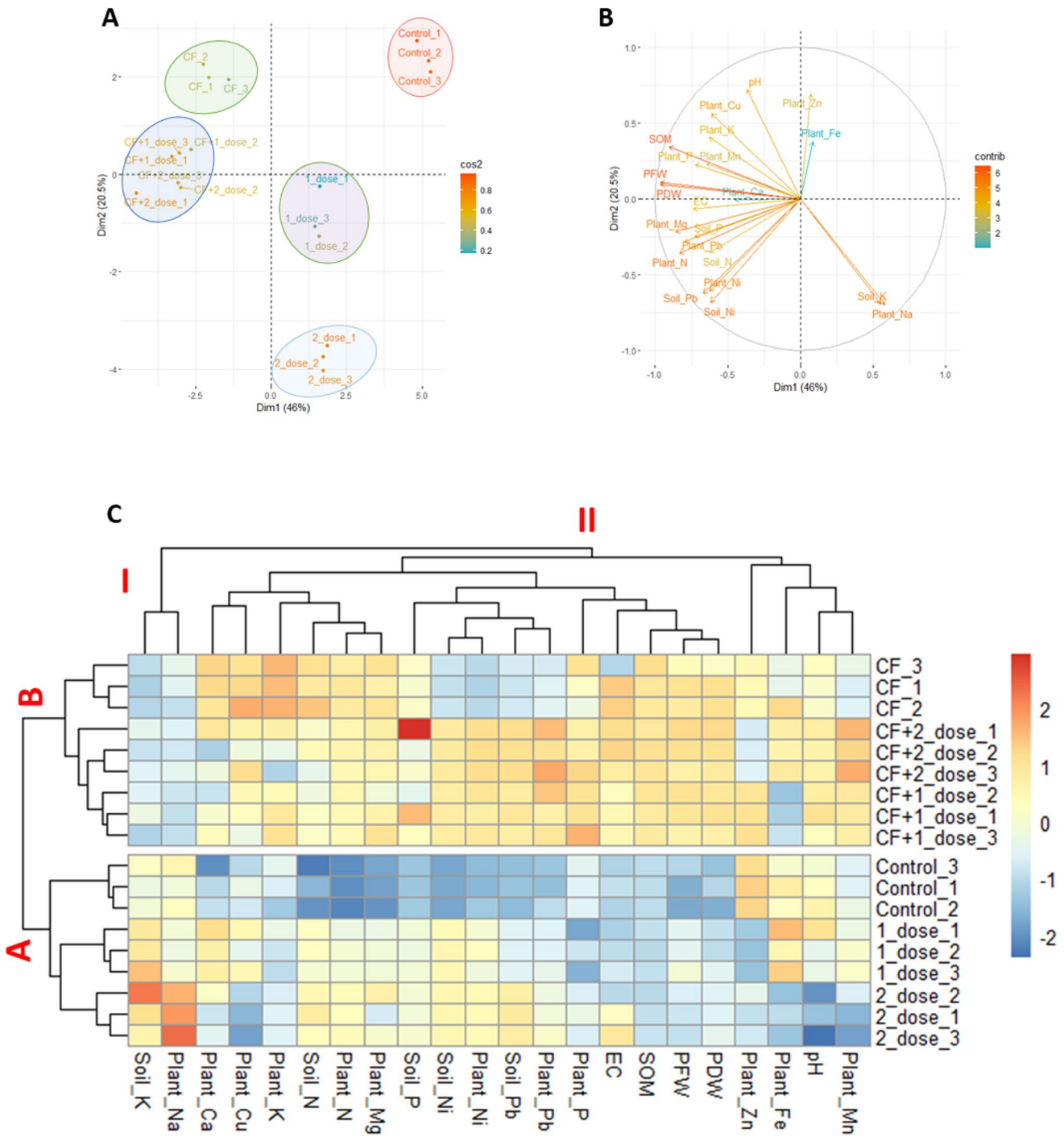


Fig. 10 (**A**) Principle component analysis (PCA) with Euclidian distance to control; (**B**) Principle component analysis (PCA) biplot based on treatments and parameters; and (**C**) Hierarchical clustering analysis (HCA) of treatments in Pasakoy station. Soil organic matter (SOM), plant fresh weight (PFW), and plant dry weight (PDW)

low TP content will directly affect microalgae growth and chlorophyll production (Znad et al. 2018). The results are consistent with those of Lutzu et al. (2021), who demonstrated that P is utilized by microalgae during culture for their growth. P removal by microalgae in wastewater can be attributed to biological absorption during their development, as stated by Mohsenpour et al. (2021). It is known that the high N: P ratio in the atomic structure of microalgae increases the release of polysaccharides that cause mucilage in the sea (Ding et al. 2021). Therefore, Pasakoy wastewater is considered to have a higher potential to produce mucilage for natural *Chlorella vulgaris* in the sea. Microalgae grown

in nutrient-rich environments such as WWTPs are known as an important environmentally friendly alternative for nutrient supply and recycling in crop cultivation (Alaviangha-vanini et al. 2024; Solovchenko et al. 2016).

Following the harvest, microalgae applications were found to have effects on various soil parameters. Especially, high doses of microalgae applications result in an increasing effect on soil pH with long-term use (Alvarez et al. 2021). It is important to monitor salinity levels by desalination in wastewater or controlled irrigation applications in the field, especially in fertilizer applications with microalgae to be obtained by using salt-rich wastewater. Although salinity is a necessary component in the microalgae growth mechanism, there are varying tolerance limits depending on the species, and *Chlorella vulgaris* has a lower salt tolerance compared to other algal species (Vo et al. 2020). Changes in SOM due to microalgae application are compatible with the studies (Alvarez et al. 2021; Guo et al. 2020). The results showed that microalgae applications can contribute to the structural development of the soils. Solé-Bundó et al. (2017) reported that microalgae contain a moderate quantity of NH_4^+-N; they may contribute to soil N content but should be regarded as soil conditioners rather than direct biofertilizers. According to Silva et al. (2015), this might be because of microalgae's capacity to mobilize presently found insoluble forms of inorganic phosphate in the soil. According to Redmile-Gordon et al. (2020), microalgae have the potential to improve the stability of soil aggregates by increasing the amount of SOM, N, and P in the soil. To sustain soil fertility, stable soil aggregates are essential because they provide the porous structure for plant growth and nutrient uptake (Ali et al. 2024). The results show that the amount of residual K at harvest has increased, which is favorable for the ongoing crop production period. Renuka et al. (2016) pointed out that soil nutritional status may be preserved with the use of microalgae in farming practices, and the findings confirmed this statement. According to Gautam et al. (2021), the use of a biofertilizer that is based on microalgae has been reported to increase the yields of crops. This results in the enhancement of height, and plant biomass with nutrient delivery and intake. *Chlorella* sp. often plays a role in wastewater treatment and is regarded as an ideal alternative for soil conditioning and delivering high nutrients (N and P) for the growth and development of plants (Ammar et al. 2022).

In parallel with its effects on soil properties, microalgae application also influenced wheat plant nutritional composition and yield-related parameters. The findings revealed that treatments using *Chlorella vulgaris* were effective for wheat growth promotion. Numerous studies have highlighted the effect of *Chlorella vulgaris* on the soil for various crops, explaining its positive effects on plant growth and yield (Cordeiro et al. 2022; Renuka et al. 2016; Suchithra et al. 2022). Dineshkumar et al. (2019) reported that using *Chlorella vulgaris* as biofertilizers through a soil leaching method increased rice yield by 20.9% and affected plant fresh weight and dry weight. *Chlorella vulgaris* was not as effective as CF on the N content of the wheat plant could include differences in the bioavailability of N from *Chlorella vulgaris* compared to CF, or potential variations in experimental conditions such as nutrient composition, environmental factors, or the specific strain of *Chlorella vulgaris* used. Additionally, the form in which N is provided by *Chlorella vulgaris* may differ from CF, affecting its uptake by the wheat plant. However, previous studies have shown that *Chlorella vulgaris* can increase N content in plants (Das et al. 2019; Silambarasan et al. 2021). Approximately 0.2% of the dry weight of a plant is composed of P, an essential nutrient for plant growth (Nosheen et al. 2021). In a study with rice plants, similar results have been reported by Rupawalla et al. (2021), which were found useful regarding the P enhancement in soils. The application of *Chlorella vulgaris* can contribute to bioremediation efforts, as it has been shown to effectively remove pollutants and excess nutrients from wastewater. This dual role as a biofertilizer and a bioremediation agent makes it a valuable asset in sustainable agriculture (Kholssi et al. 2022). Studies have demonstrated that the use of microalgae can lead to significant reductions in N and P levels in agricultural runoff, thereby mitigating the impacts of eutrophication in aquatic ecosystems (Abdelfattah et al. 2023; Chen et al. 2020). The K content of the wheat was found to be higher in the treatments in which *Chlorella vulgaris* was applied together with CF rather than microalgae alone similar to the earlier studies (Supraja et al. 2020; Suchithra et al. 2022). In the plants, the combined application of microalgae with CF increased the Ca content more than microalgae alone. The Ca content in wheat plants ranged from 0.2 to 0.5%, which is sufficient for the plant (Benton Jones 2018). The data indicate that the Ca levels were adequate in all treatments across both experiments. Mg levels between 0.15% and 0.5% are considered "adequate" (Benton Jones 2018). In both experiments, Mg was "adequate" in plants, except for the control treatment. In treatments where *Chlorella vulgaris* was applied together with CF, the Na content in plants was lower than in treatments with *Chlorella vulgaris* alone.

Research indicates that *Chlorella vulgaris* is effective in improving plant nutrient content in various crops. For instance, the use of *Chlorella vulgaris* significantly increased the nutrient content, including K and Ca, in garden rocket and lettuce seedlings, leading to enhanced growth and yield (Sadak Turhan et al. 2022). Similarly, microalgae biomass is a rich source of macroelements, which can enhance soil properties and plant growth (Ekinci et al.

2019). The physiological activities facilitated by these nutrients include cellular organization and metabolism, which are vital for plant development (Godlewska et al. 2019). The slow-release nature of nutrients from microalgae also plays a crucial role in sustaining plant growth over time. Mückschel's research on N use efficiency revealed that the organic N from microalgae is released more slowly compared to conventional fertilizers, which can be beneficial for crops (Mückschel et al. 2023). This slow release allows for a more consistent nutrient supply, which is essential for maintaining optimal growth conditions.

Besides its impact on macroelement uptake, microalgae application also influenced the microelement and potential heavy metal dynamics in wheat plants. In addition to N and P, *Chlorella vulgaris* is also a source of essential microelements that play significant roles in plant metabolism. The presence of microelements such as Zn, Cu, and Mn in *Chlorella vulgaris* further contributes to its effectiveness as a biofertilizer. *Chlorella vulgaris* contains a diverse range of microelements that are beneficial for plant growth (Vildanova et al. 2023). Soil fertility and plant growth are enhanced by the release of microelements during the microbial decomposition and mineralization of *Chlorella vulgaris*. This process ultimately stimulates microbial activity, accelerating the degradation of organic matter and nutrient cycling, thereby making nutrients more available to plants (Agwa et al. 2018). Additionally, *Chlorella vulgaris* induces the expression of biosynthetic genes responsible for nutrient uptake and increases the nutrient content of crops (Sadak Turhan et al. 2022). Microbial interactions, biomass composition, and soil dynamics contribute to the bioavailability of its nutrients, which can be absorbed by plants, collectively improving nutrient uptake and promoting plant growth.

Tolpeznikaite et al. (2021) characterized the bioactive compounds in *Chlorella vulgaris* and found that it contains various microelements, including Fe, Mn, Zn, and Cu. These microelements are crucial for enzymatic reactions, chlorophyll synthesis, and overall plant health. The presence of these nutrients in *Chlorella vulgaris* can enhance the physiological processes in wheat, leading to increased resilience against environmental stresses. For instance, Fe is essential for chlorophyll formation, while zinc is involved in hormone production and enzyme function. The availability of these microelements in the soil, facilitated by the application of *Chlorella vulgaris*, can significantly influence the growth and yield of wheat crops. Dębowski et al. (2018) noted that the biomass produced by *Chlorella vulgaris* can effectively remove plant nutrients from anaerobic digestion effluents, thereby improving soil quality and fertility.

Heavy metals are known as "conservative pollutants," which means that they cannot be reduced by bacteria or any other organisms and may thus be found in the environment (Ammar et al. 2022). There is a considerable amount of research on the long-term use of chemical fertilizers causing an increase in heavy metals in soil and plants (Liu et al. 2023; Narayanaswamy et al. 2024). It is known that microalgae can adsorb heavy metals from wastewater as a result of wastewater treatment (Geremia et al. 2021; Narayanaswamy et al. 2024; Sultana et al. 2020). Heavy metals, including Ni and Pb, are known to have toxic effects on plant growth. They can disrupt physiological processes, leading to reduced germination rates, stunted growth, and lower yields in crops such as wheat (Rizwan et al. 2016; Stanis˘ić Stojić et al. 2016). For instance, Pb exposure has been shown to inhibit root elongation and affect nutrient uptake, which is critical for wheat development (Rahman et al. 2023). Similarly, Ni toxicity can lead to chlorosis and necrosis in plant tissues, further compromising growth and productivity (Hassan et al. 2019). While utilizing treated wastewater for microalgae cultivation presents a promising solution, it is essential to assess the microalgae biomass for contamination with heavy metals, as well as evaluate its environmental impacts on soil and toxicity before applying it in agricultural practices (de Paula Pereira et al. 2023).

5 Conclusion

Microalgae play a cruial role in wastewater treatment and agricultural sustainability. This study demonstrates that microalgae effectively removed nitrogen (N) and phosphorus (P) from wastewater, contributing to the reduction of mucilage formation in Istanbul Bosphorus. Additionally, the microalgae-derived biomass enhances soil fertility and promotes wheat growth, particularly when combined with chemical fertilizer. Furthermore, the high adsorption capacity of microalgae for heavy metals emphasizes the necessity of pre-treatment before agricultural use. This study highlights the potential of microalgae in supporting a a circular bioeconomy by integrating wastewater treatment with biofertilizer production. Future research is needed to address the complexities of pollutant mixtures in natural environment and to further optimize microalgae-based strategies for developing sustainable pollution management systems.

Acknowledgements This work was financially supported by the Scientific and Technological Research Council of Türkiye [Project number: TUBİTAK-121G131]". The authors are grateful to Bilgin International Informatics Industry and Trade Inc. for the efforts of sophisticated ideas and also thank the Ankara University Biology Department and the Republic of Türkiye Ministry of Agriculture and Forestry, Central Research Institute of Soil Fertilizer and Water Resources for the use of the laboratory facility.

Author Contributions Muhittin Onur Akca: Data curation; Formal analysis; Investigation; Project administration; Resources; Software; Visualization; Writing – original draft; Writing – review & editing.

Selen Deviren Saygin: Data curation; Investigation; Project administration; Methodology; Writing – original draft; Writing – review & editing. Sefika Arslan: Formal analysis, Project administration. Adem Bilgin: Data curation; Formal analysis; Investigation, Writing – review & editing. Gunay Erpul: Data curation; Investigation; Project administration; Resources; Software; Writing – original draft; Writing – review & editing.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Data Availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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