IRSTI 34.27.23 https://doi.org/10.26577/bb2025103211

N. Akmukhanova[1]*, S. Seiilbek[1], R. Bakytzhan[1], G. Domash[1], S. Amin[1]

Al-Farabi Kazakh National University, Almaty, Kazakhstan
*e-mail: akmukhanova.nurziya@gmail.com

BIODIVERSITY OF MICROALGAE AND CYANOBACTERIA IN COTTON FIELD ECOSYSTEMS OF THE TURKESTAN REGION

This study explores the biodiversity of microalgae and cyanobacteria in cotton field ecosystems of the Turkestan Region, Kazakhstan. Soil sample analysis identified 45 species of microalgae and cyanobacteria, with cyanobacteria–particularly those belonging to the genera *Nostoc* and *Anabaena*–showing the highest diversity. Furthermore, four pure cultures were isolated using the enrichment culture method, allowing detailed examination of their morphological traits and tolerance to pesticides. These organisms play important ecological roles, especially in nutrient cycling and nitrogen fixation, contributing to soil fertility and sustainability of agroecosystems. To evaluate photosynthetic activity under stress conditions, an experiment was conducted using the widely used herbicide atrazine. The results revealed species-specific differences in pesticide resistance, highlighting the resilience of some isolates. The findings underscore the potential application of these native microalgae and cyanobacteria in bioremediation of pesticide-contaminated soils. Moreover, due to their sensitivity and adaptive responses, they can serve as valuable bioindicators of chemical pollution. By expanding knowledge of local microbial biodiversity, this research lays the groundwork for utilizing autotrophic microorganisms in bioindication and agroecological management.

Keywords: microalgae, cyanobacteria, biodiversity, pesticides, atrazine.

Н.Р. Акмуханова[1*], С.Н. Сейілбек[1], Р.Ә. Бақытжан[1], Г.С. Домаш[1], С. Амин[1]

Әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан
*e-mail: akmukhanova.nurziya@gmail.com

Түркістан облысы мақта алқабының экожүйелеріндегі микробалдырлар мен цианобактериялардың биоалуантүрлілігі

Бұл зерттеуде Қазақстанның Түркістан облысындағы мақта алқаптарының агрожүйелерінде тіршілік ететін микробалдырлар мен цианобактериялардың биоалуантүрлілігі зерттелді. Топырақ үлгілерін талдау нәтижесінде микробалдырлар мен цианобактериялардың 45 түрі анықталды, олардың ішінде *Nostoc* және *Anabaena* туыстарына жататын цианобактериялар алуан түрлілігімен ерекшеленді. Жинақы дақыл әдісі арқылы төрт таза дақыл бөлініп алынып, олардың морфологиялық белгілері мен пестицидтерге төзімділігі жан-жақты зерттелді. Бұл организмдер экожүйелерде, әсіресе биогеохимиялық циклдер мен азот фиксациясында маңызды рөл атқарады, бұл топырақ құнарлылығын арттыруға және ауыл шаруашылығының тұрақтылығына ықпал етеді. Атразин гербицидін пайдалана отырып, стресс жағдайындағы фотосинтетикалық белсенділікті бағалау мақсатында тәжірибе жүргізілді. Нәтижелер пестицидтерге төзімділікте түрге тән айырмашылықтарды көрсетті. Алынған дақылдар пестицидтермен ластанған топырақтарды биоремедиациялау үшін қолдануға жарамды және химиялық ластанудың биоиндикаторы ретінде пайдаланылуы мүмкін. Жергілікті микробтық биоалуантүрлілік туралы білімді тереңдете отырып, бұл зерттеу автотрофты микроағзаларды биоиндикация мен агроэкологиялық басқаруда қолданудың негізін қалайды.

Түйін сөздер: микробалдырлар, цианобактериялар, биоалуантүрлілік, пестицидтер, атразин.

Н.Р. Акмуханова[1*], С.Н. Сейілбек[1], Р.Ә. Бақытжан[1],
Г.С. Домаш[1], С. Амин[1]

Казахский национальный университет имени аль-Фараби, Алматы, Казахстан
*e-mail: akmukhanova.nurziya@gmail.com

Видовое разнообразие микроводорослей и цианобактерий в экосистемах хлопковых полей Туркестанской области

В настоящем исследовании рассматривается биоразнообразие микроводорослей и цианобактерий, обитающих в агроэкосистемах хлопковых полей Туркестанской области, Казахстан. В результате анализа образцов почвы было выявлено 45 видов микроводорослей и цианобактерий, при этом наибольшее разнообразие наблюдалось среди цианобактерий, в частности, родов *Nostoc* и *Anabaena*. С использованием метода накопительных культур были выделены четыре чистые культуры, что позволило детально изучить их морфологические характеристики и устойчивость к пестицидам. Эти организмы играют важную роль в экосистемах, особенно в биогеохимических циклах и фиксации азота, что способствует повышению плодородия почвы и устойчивости сельского хозяйства. Для оценки фотосинтетической активности в условиях стрессового воздействия был проведён эксперимент с применением гербицида атразина. Полученные результаты показали видоспецифические различия в устойчивости к пестицидам. Исследуемые штаммы обладают потенциалом для применения в биоремедиации загрязнённых пестицидами почв, а также могут служить биоиндикаторами химического загрязнения. Расширяя знания о местном микробном биоразнообразии, данное исследование закладывает основу для использования автотрофных микроорганизмов в биоиндикации и агроэкологическом управлении.

Ключевые слова: микроводоросли, цианобактерии, биоразнообразие, пестициды, атразин.

1. Introduction

Cotton fields, despite their considerable economic importance and substantial contribution to the textile industry, pose a significant environmental challenge. The main environmental concerns associated with cotton cultivation include the use of pesticides and chemical fertilizers, water resource management, soil salinization and erosion, carbon footprint, as well as public health impacts and the degradation of natural ecosystems [1]. Intensive application of pesticides and chemical fertilizers on cotton fields leads to environmental pollution, as these substances can penetrate the soil and water resources, thereby adversely affecting biodiversity and ecosystem health [2].

Considering these environmental challenges, the Turkestan Region in southern Kazakhstan, recognized as the northernmost cotton-producing territory in the world, faces unique problems. Each year, medium-fiber cotton is cultivated here on an area of 115,000–125,000 hectares [3,4], leading to additional environmental threats such as soil salinization, drought, pests, and diseases. Pesticides enter the environment through various pathways after their application to agricultural crops or soil. Many pesticides contain chemical compounds that can be harmful or even lethal to humans, animals, and plants. Global pesticide consumption in agriculture is projected to increase to 4.5 million metric tons by 2027 [5]. While the majority of agricultural pesticides are used in North and South America, pesticide usage in Kazakhstan, as in many other countries, is rising. These chemicals are essential for increasing crop yields and ensuring regional food security. Currently, approximately 1,021 trade names of pesticides with various applications and uses are registered in Kazakhstan [6]. Each year, the list of registered pesticides expands by 15–20 new formulations. The predominant classes of pesticides in use include insecticides (172), fungicides (125), and herbicides (520). These compounds are often detected at levels exceeding legally established limits or environmental standards [7].

Furthermore, an inventory of obsolete pesticides in Kazakhstan has identified over 700 storage sites and 15 burial facilities. The accumulation of outdated pesticide stocks not only poses risks to public health and the environment but also contributes to the contamination of natural resources and hinders socio-economic development. Consequently, adherence to global standards and regulatory requirements for highly hazardous pesticides remains a pressing issue.

In response to these issues, the algal flora of cotton fields constitutes an important component of the ecosystem. Microalgae and cyanobacteria in soils play a crucial role in maintaining soil health and fertility. These photosynthetic microorganisms play a role in carbon and nitrogen fixation, improve soil structure, and stimulate plant development [8;9]. In addition, they generate valuable biomass, phytohormones, and other bioactive compounds that enhance soil ecological conditions and aid in the suppression of plant diseases [8].

In addition, microalgae and cyanobacteria play an essential role in sustaining ecological balance within agricultural ecosystems by taking part in nutrient cycling, enhancing soil structure, and fostering biodiversity. Their ability to degrade toxic substances such as insecticides and herbicides makes them crucial for increasing the resilience of ecosystems to chemical contamination [10]. The response of microalgae to pesticides varies among species: some exhibit resistance, while others are more sensitive. These differences are explained by their ecophysiological characteristics, which are especially notable among Arctic and temperate microalgae [11]. Meanwhile, several microalgal strains, including *Chlorella* and *Scenedesmus*, efficiently remove pesticides from the environment through biodegradation, with certain strains achieving over 90% pesticide removal efficiency. This underscores their potential for use in bioremediation [12].

The aim of this study is to examine the species diversity of microalgae and cyanobacteria in cotton field ecosystems of the Turkestan Region and to isolate and characterize strains that exhibit resistance to pesticides. Examining microalgae and cyanobacteria in this context will enable an assessment of their ecological role and potential in maintaining the health and resilience of cotton field ecosystems under intensive agricultural conditions.

2. Materials and methods

Sampling

Soil samples were collected from cotton fields located in the village of Sholpankuduk, Zhetisay district, Turkestan Region (40.945160, 68.105845) during the spring and summer of 2024. A total of 28 algological samples were collected from sites where algal growth was visibly pronounced. Each sample was accurately labeled with the corresponding sample number, date and location of collection, and the name of the collector. Field sampling and subsequent laboratory analysis were conducted in accordance with established algological methodologies.

Each soil sample was subjected to microscopic examination using "Premiere" and "MicrosAustria" light microscopes at magnifications of 40× to 100×. For each of the five microscope slides prepared, a minimum of 30–40 fields of view were observed. Microalgae and cyanobacteria were identified in both their native and fixed forms, with formaldehyde and iodine solutions used as fixatives. Taxonomic determinations of microalgae and cyanobacteria were carried out according to standard taxonomic literature [13; 14] and updated information from AlgaeBase [15], CyanoDB [16], as well as relevant modern taxonomic studies.

Isolation of Microalgae and Cyanobacterial Strains

For the preparation of enrichment cultures, the collected material was inoculated into flasks or test tubes containing sterile liquid nutrient medium, ensuring that the medium volume did not exceed 1/3–1/4 of the flask volume. The inoculated culture vessels were incubated at 25°C under constant artificial light supplied by Flora Led 35 D120 lamps, with an intensity of 80 μmol photons·m^{-2}·s^{-1}. The nutrient media used to obtain enrichment cultures of microalgae and cyanobacteria included Zarrouk's, Gromov's, BG-11, Tamiya, and Prat.

After the cultivation period, 1 mL of the microalgal and cyanobacterial suspension was transferred onto Petri dishes containing solid nutrient agar–either directly or after several subculturing steps, depending on the purity of the enrichment culture. The suspension was spread across the agar surface using a sterile spatula. The Petri dishes were then placed under light to allow colony formation. From each developed colony, a portion of the culture was taken with a loop and transferred to fresh liquid medium or a slant. By repeatedly isolating material from a single colony and employing a sufficiently diluted suspension for inoculation, it can be assumed that each colony arises from a single cell [17]. The purity of the microalgal and cyanobacterial cultures was verified before and after each stage of the procedure through thorough microscopic examination using phase-contrast illumination (Carl Zeiss Axioskop 40, Germany). All procedures were conducted under aseptic conditions with sterile materials. The cultures were maintained at 22–24°C under constant illumination.

Methodology for Determining the Pesticide Resistance of Microalgae and Cyanobacteria

Microalgae and cyanobacteria were initially grown for 8–10 days in 500 mL conical flasks containing the appropriate nutrient media, under constant artificial lighting from Flora Led 35 D120 lamps (80 μmol photons·m^{-2}·s^{-1}) at a temperature of 22–24°C. The growth of microalgae was monitored by recording changes in their cell density using a Goryaev counting chamber [18]. Once the cultures reached the exponential phase, they were transferred to 1 L Erlenmeyer flasks with an initial cell density of 2.5×10^5 cells/mL. After transfer, the cells were exposed to different concentrations of the pesticide atrazine for 72 hours. To ensure statistical reliability of the results, the experiment was conducted in triplicate for each concentration of the pesticide.

To evaluate the response of microalgae to pesticides, both the cell density and the maximum quantum yield of the photochemical reactions (FV/FM) were measured at the beginning of the experiment (time zero) and after 72 hours. Fluorescence intensity was also recorded as an indicator of photosynthetic activity. Rapid chlorophyll a fluorescence induction curves in intact cyanobacterial cultures were recorded using Aquapen–C 100 fluorometers (PSI, Czech Republic) under actinic light with a wavelength of 630 nm and an intensity of 1500 μmol photons·m^{-2}·s^{-1}. The obtained curves were analyzed using the JIP-test methodology [19], which includes the following parameters: fluorescence intensity at 20 μs (FO), 2 ms (FJ), 30 ms (FI), 6 s (F6s), as well as FP (FM, the maximum fluorescence intensity) and M0 (the area above the OJIP kinetic curve and below FM). Based on these measurements, the following indicators were calculated:

FV = FM – FO, representing the maximum variable fluorescence;

FV/FM, indicating the maximum quantum yield of the primary photochemical reaction in open PS II reaction centers (FV/FM = φPo).

All measurements were carried out in at least five replicates.

3. Results and discussion

Algal Flora of Cotton Field Ecosystems in the Turkestan Region

The Turkestan Region is characterized by diverse soil types, including dark and light sierozems (grey soils), meadow-sierozems, and meadow soils. Irrigated lands in the region often have low nutrient content. According to the Ministry of Agriculture of the Republic of Kazakhstan, the soils in this area include non-saline soils (69%), slightly saline (13%), moderately saline (11%), and strongly saline (7%). The largest number of strongly and severely saline lands has been recorded in the Zhetisay, Otyrar, Shardara, and Maktaaral districts. Based on their meliorative status, the region's irrigated lands are classified as good (185.5 thousand ha), satisfactory (166.6 thousand ha), and unsatisfactory (222.3 thousand ha) (Official Internet Resource of the Republic of Kazakhstan).

Cotton cultivation is actively developing in the Zhetisay district. In 2024, more than 40 thousand hectares of cotton were sown in this area, and by October, over 50 thousand tons of the "white gold" had been harvested. To enhance crop yields and promote more efficient water use, innovative water-saving methods such as drip irrigation are being implemented. Nevertheless, soil degradation–especially salinization–continues to pose a significant threat to agriculture in the region. Salinization not only lowers crop productivity but can also lead to the conversion of fertile soils into saline-affected lands. The cotton field soils in the village of Sholpankuduk, Maktalynsky rural district, Zhetisay district of the Turkestan Region, are significantly impacted by pesticides. The intensive use of chemical plant protection agents–such as insecticides, herbicides, and fungicides–stems from the need to combat pests and weeds common to this crop. However, prolonged pesticide application negatively affects soil quality.

In this study, 45 species of microalgae and cyanobacteria were identified from soil samples (Fig. 1). These included five species of *Xanthophyta* (yellow-green algae), 19 species of cyanobacteria, seven species of *Bacillariophyta* (diatoms), and 14 species of green algae. The most commonly encountered species were *Phormidium autumnale*, *Nitzschia palea*, *Chlorella vulgaris*, *Nostoc linckia*, and *Anabaena flos-aguae*. These species, belonging to different taxonomic groups, play important roles in various soil processes. *Chlorella vulgaris* is an important component in food webs and nutrient cycling. Cyanobacteria were found to be the most diverse group, comprising 19 species. The family *Nostocaceae*, which includes the genera *Anabaena* and *Nostoc*, exhibited the highest species diversity. Heterocystous forms such as *Anabaena cylindrica* and *Nostoc commune* constituted the majority of the cyanobacterial community. These organisms play a crucial role in biogeochemical cycles, especially nitrogen fixation, which is critically important for agriculture.

The results of the study, based on collected soil samples, revealed a significant diversity of microalgae and cyanobacteria inhabiting this ecosystem. The observed species diversity of microalgae and cyanobacteria highlights their importance for ecosystem processes and soil fertility maintenance.

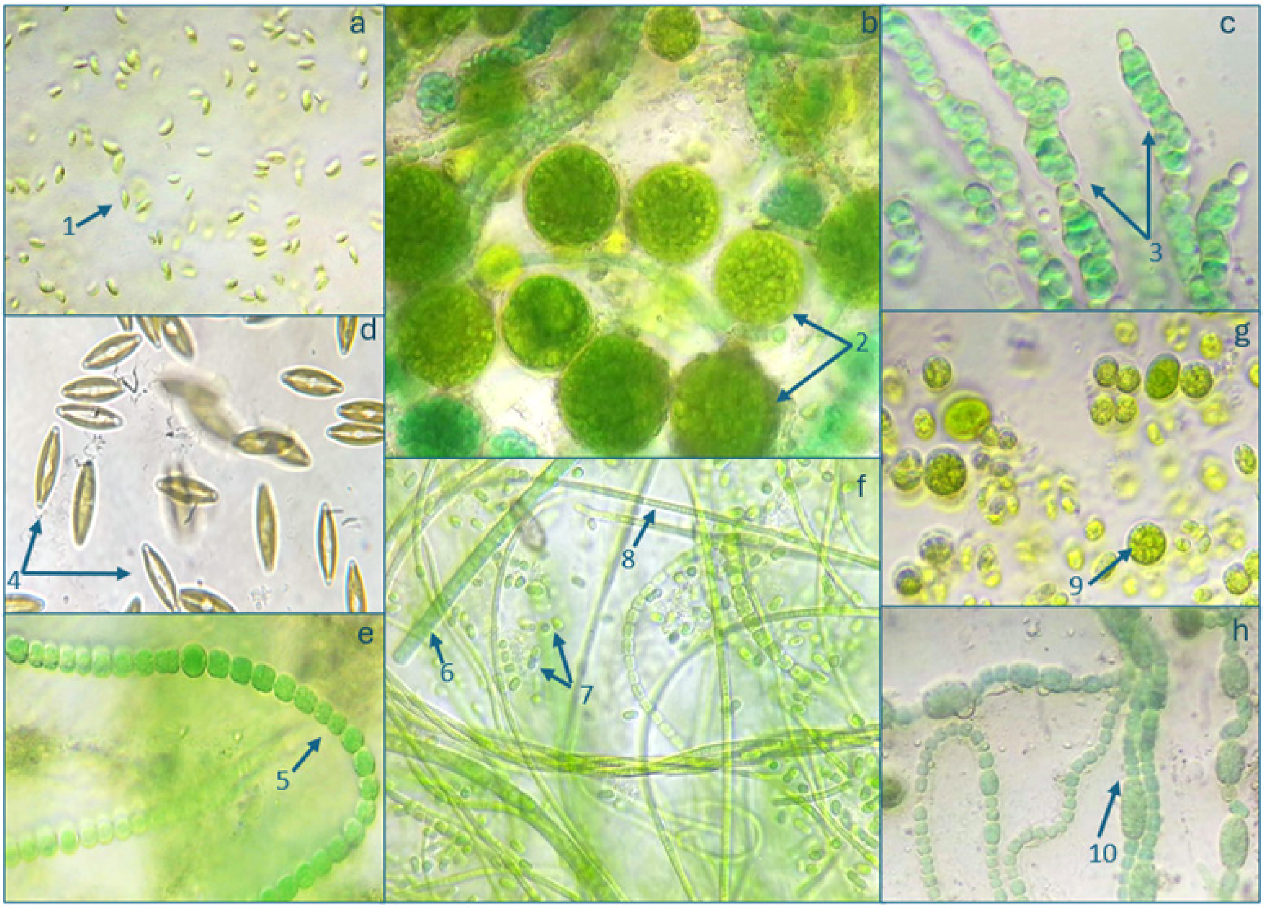

Figure 1 – Biodiversity of Microalgae in the Ecosystems of Cotton Fields in the Turkestan Region. a-h-specimens of the studied samples. Numbers indicate: 1- *Dunaliella*, 2-*Chlorococcum,* 3-*Nostoc*, 4-*Navicula*, 5-*Nostoc*, 6-*Phormidium*, 7-*Synechococcus, 8-Oscillatoria, 9-Chlorella, 10-Anabaena*

Isolation of Pure Cyanobacterial Cultures

Using the enrichment culture method based on collected soil samples, four algologically and bacteriologically pure cultures of cyanobacteria and microalgae were isolated. The morphological study of pure microalgae and cyanobacteria revealed the following characteristics: the culture *Chlorella vulgaris Sp – T24* is a unicellular green microalga with a spherical shape, measuring 2-10 μm in diameter. The cells have a smooth cell wall and contain a single large chloroplast, which gives them a bright green color (Fig. 2). *Scenedesmus Sp – T24* is a colonial green alga forming groups of 2-4 cells arranged in linear colonies. The cells are oval or cylindrical, measuring 5-15 μm in length and 2-4 μm in width (Fig. 2). *Synechococcus Sp – D24* is a unicellular cyanobacterium with elongated cylindrical cells, measuring 2-6 μm in length and 1-2 μm in width. The cells are blue-green in color, and reproduction occurs through binary fission (Fig. 2). *Nostoc Sp – D24* is a colonial cyanobacterium forming filamentous trichomes up to several hundred micrometers in length. The cells are spherical or oval, with a diameter of 3-6 μm, and are surrounded by a mucilaginous sheath. The trichomes include heterocysts, which are specialized cells involved in nitrogen fixation (Fig. 2). The isolated cultures demonstrated good growth on Tamiya, Gromov, and BG-11 nutrient media.

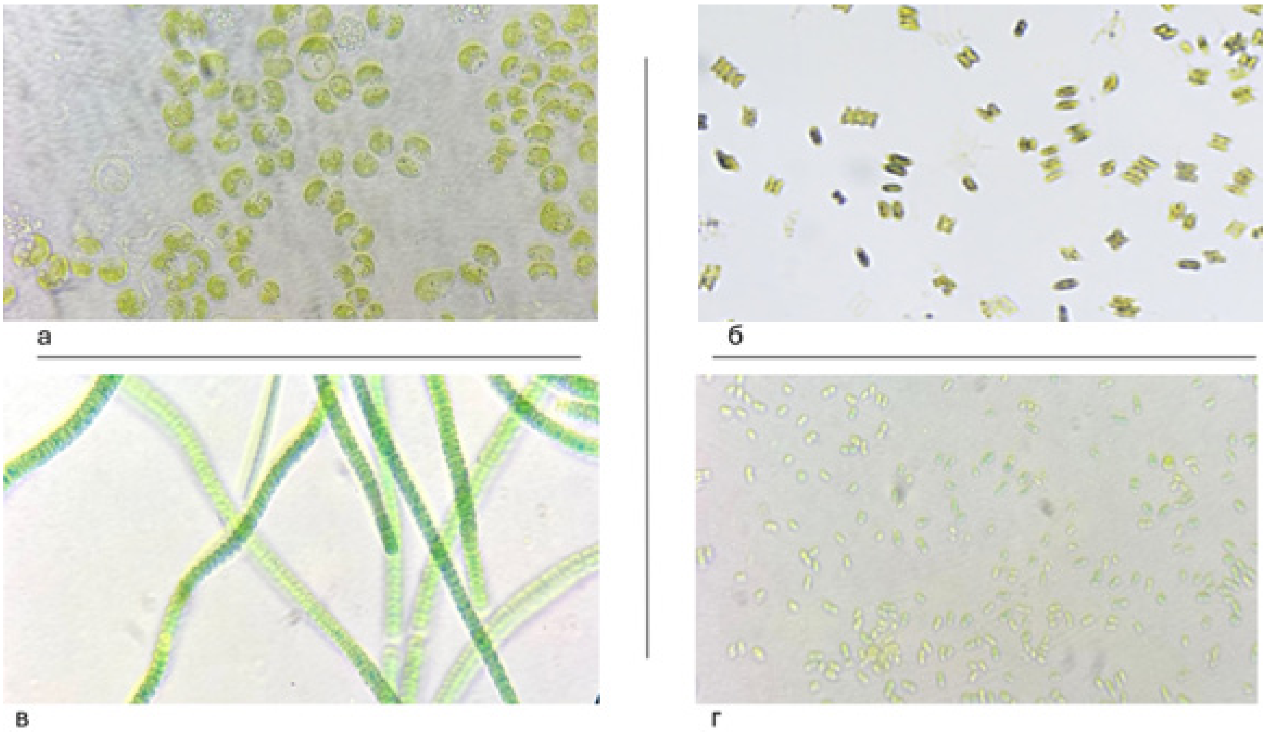

Figure 2 – Microphotographs of Isolated Microalgae and Cyanobacteria from the Soils of Cotton Fields in the Turkestan Region. a – *Chlorella vulgaris Sp-T24*, b – *Scenedesmus Sp-T24*, c – *Nostoc Sp-D24*, d – *Synechococcus Sp-D24*.

Determination of Microalgae Resistance to Pesticides

To assess the resistance of microalgae (*Chlorella vulgaris Sp-T24*, *Scenedesmus Sp-T24*, *Synechococcus Sp-D24*, *Nostoc Sp-D24*) to atrazine, an experiment was conducted in which the cultures were exposed to various concentrations of atrazine (0.1 µg/L, 1 µg/L, 10 µg/L) for 72 hours. For each microalgae species, the following parameters were measured: maximum quantum yield of photochemical reactions (FV/FM), fluorescence intensity as an indicator of photosynthetic activity, and growth inhibition expressed as a percentage reduction in biomass (Table 1).

Table 1 – Effects of Different Atrazine Concentrations on Key Parameters of Microalgae

Atrazine concentration (µg/L)	Microalgal species	FV/FM (φPo)	Fluorescence intensity (%)	Growth inhibition (%)
0 (control)	*Chlorella vulgaris* Sp-T24	0.48	100	0
0.1	*Chlorella vulgaris* Sp-T24	0.46	95	5
1	*Chlorella vulgaris* Sp-T24	0.41	80	20
10	*Chlorella vulgaris* Sp-T24	0.35	50	50
0 (control)	*Scenedesmus* Sp-T24	0.44	100	0
0.1	*Scenedesmus* Sp-T24	0.38	85	15
1	*Scenedesmus* Sp-T24	0.35	60	40
10	*Scenedesmus* Sp-T24	0.25	30	70
0 (control)	*Synechococcus* Sp-D24	0.47	100	0
0.1	*Synechococcus* Sp-D24	0.45	90	10
1	*Synechococcus* Sp-D24	0.42	75	25

Continuation of the table

Atrazine concentration (μg/L)	Microalgal species	FV/FM (φPo)	Fluorescence intensity (%)	Growth inhibition (%)
10	*Synechococcus* Sp-D24	0.38	60	40
0 (control)	*Nostoc* Sp-D24	0.46	100	0
0.1	*Nostoc* Sp-D24	0.35	70	30
1	*Nostoc* Sp-D24	0.30	50	50
10	*Nostoc* Sp-D24	0.20	20	80

The experimental data demonstrate that atrazine exhibits an inhibitory effect on the photosynthetic activity and growth of all studied microalgal species. The most significant reduction in fluorescence intensity and FV/FM was observed at an atrazine concentration of 10 μg/L, confirming its toxicity to these organisms. At the same time, at concentrations of 0.1 μg/L and 1 μg/L, changes in the parameters were less pronounced, which may indicate a lower toxicity of these concentration levels for the studied microalgal species.

The greatest inhibition of growth and photosynthesis was observed in *Scenedesmus* Sp-T24 and *Nostoc* Sp-D24 under the influence of atrazine, indicating their sensitivity to the pesticide. In contrast, *Chlorella vulgaris* Sp-T24 and *Synechococcus* Sp-D24 exhibited higher tolerance to atrazine compared to the other cultures, maintaining a significant portion of their photosynthetic activity even at increased pesticide concentrations. *Nostoc* Sp-D24 proved to be the most sensitive species, making it a potential indicator for assessing pesticide impacts on ecosystems.

The maximum quantum yield of primary photochemical reactions (FV/FM, φPo) in *Chlorella vulgaris* Sp-T24 and *Synechococcus* Sp-D24 remained at a high level (0.46–0.45), indicating their ability to maintain photosynthetic activity under low atrazine concentrations (Table 1). In contrast, *Scenedesmus* Sp-T24 showed a slight decrease in FV/FM even at an atrazine concentration of 0.1 μg/L, suggesting its lower tolerance.

The analysis of the results revealed a significant decrease in fluorescence intensity in all studied microalgal cultures with increasing atrazine concentrations. This reduction is associated with damage to the photosynthetic apparatus caused by the toxic effects of the pesticide. A more pronounced decline in fluorescence was observed in *Scenedesmus* Sp-T24 and *Nostoc* Sp-D24, confirming their heightened vulnerability. In contrast, *Chlorella vulgaris* Sp-T24 and *Synechococcus* Sp-D24 demonstrated higher tolerance to atrazine. This could be attributed to physiological traits such as enhanced detoxification mechanisms or more effective protection of the photosynthetic apparatus.

Scenedesmus Sp-T24 and *Nostoc* Sp-D24 exhibited the greatest sensitivity to atrazine, indicating a lower adaptation to pesticide-induced stress. The findings of this study emphasize the differences in microalgal sensitivity to atrazine. More tolerant species, such as *Chlorella vulgaris* Sp-T24 and *Synechococcus* Sp-D24, may have potential for biotechnological applications, including bioremediation in pesticide-contaminated environments. In contrast, the most sensitive species, *Scenedesmus* Sp-T24 and *Nostoc* Sp-D24, can serve as bioindicators for assessing pesticide pollution in aquatic ecosystems.

The study of microalgae and cyanobacteria inhabiting the ecosystems of cotton fields in the Turkestan region highlights the diversity of organisms that play a crucial role in maintaining ecosystem processes. In particular, the identification of 45 species of microalgae and cyanobacteria, including species such as *Chlorella vulgaris*, *Nostoc linckia*, and *Anabaena flos-aquae*, confirms the presence of diverse taxonomic groups within these ecosystems. These microorganisms play a key role in sustaining soil fertility and supporting biogeochemical cycles, including nitrogen fixation [20; 21]. Cyanobacteria belonging to the family *Nostocaceae*, including *Anabaena cylindrica* and *Nostoc commune*, play a crucial role in agroecosystems by improving soil quality through atmospheric nitrogen fixation, which in turn boosts crop productivity in nitrogen-poor soils [22].

Cyanobacteria of the *Nostocaceae* family play a crucial role in cotton cultivation by promoting plant growth and controlling soil-borne pathogens. Studies have shown that *Nostoc* species can effectively inhibit *Fusarium oxysporum* and *Rhizoctonia solani*, increasing cotton seedling survival and yield [23;24]. These cyanobacteria also act as biofertilizers, fixing nitrogen in paddy fields and potentially in cotton fields [25; 26]. However, the use of synthetic nitrogen fertilizers negatively impacts the diversity of nitrogen-fixing cyanobacteria [25]. Research suggests that early-appearing, efficient nitrogen-fixers should be used as alternatives to synthetic fertilizers for sustainable agriculture [25]. Additionally, cyanobacteria have shown potential in pesticide biodegradation and produce bioactive compounds like ammonia and enzymes that contribute to their effectiveness in controlling fungal diseases in cotton [24].

An important aspect of the study is the impact of pesticides, specifically atrazine, on the photosynthetic activity of microalgae. Atrazine exhibited toxic effects on photosynthesis, as evidenced by reduced fluorescence intensity and photochemical activity across all studied species. The research demonstrated that *Chlorella vulgaris* and *Synechococcus* exhibited higher tolerance to atrazine compared to *Scenedesmus* and *Nostoc*, which displayed the most pronounced sensitivity to the pesticide. These findings could have significant ecological implications, as they emphasize the importance of certain species' resilience to chemical pollution, which can be leveraged for developing environmentally safe bioremediation methods [27; 28]. Studies have investigated the effects of atrazine, a widely used herbicide, on various algal species. Chlorella vulgaris demonstrated moderate tolerance to atrazine, with EC50 values ranging from 42-125 µg/L [29]. However, C. vulgaris exhibited significant physiological and genetic responses to atrazine exposure, including reduced photosystem gene transcription and increased antioxidant enzyme activity [30]. Comparatively, *Scenedesmus acutus* and *Pseudanabaena galeata* showed higher sensitivity to atrazine, with 96-hour EbC50 values of 0.014 mg/L for both species [31]. Interestingly, some algal strains, such as Franceia sp., displayed notably higher atrazine tolerance, with EC50 values ranging from 430-774 µg/L [29].

These findings suggest that atrazine tolerance varies significantly among algal species and strains, with potential implications for aquatic ecosystem dynamics in atrazine-contaminated environments. Bioremediation has emerged as an environmentally friendly and cost-effective approach for pesticide decontamination [32]. Various microorganisms, including bacteria, fungi, and algae, have been identified for their ability to degrade pesticides [33]. These microbes utilize pesticides as nutrients, breaking them down into non-toxic molecules through processes like mineralization and co-metabolism [33]. Enzymes play a crucial role in pesticide bioremediation, influencing their modes of action and environmental fates [34]. Factors such as pesticide type, microorganism species, temperature, humidity, and acidity affect the degradation process [33].

At the same time, highly sensitive species can serve as indicators of pesticide contamination, offering potential applications in monitoring soil and aquatic ecosystem quality.These organisms respond quickly to environmental changes, making them ideal for assessing toxicity and providing early warning signals of pollution [35].

Conclusion

This study highlights the ecological and biotechnological importance of microalgae and cyanobacteria in cotton field ecosystems of the Turkestan region. The identification of 45 species demonstrates their taxonomic richness and functional roles, particularly in nitrogen fixation and soil fertility enhancement. Species of the Nostocaceae family not only contribute to nutrient cycling but also promote plant growth and suppress soil-borne pathogens, making them valuable for sustainable agriculture. The assessment of atrazine toxicity revealed varying sensitivities among species, with *Chlorella vulgaris* Sp-T24 and *Synechococcus* Sp-D24 showing higher tolerance than *Scenedesmus* Sp-T24 and *Nostoc* Sp-D24. These findings suggest potential for using tolerant strains in bioremediation and sensitive species as indicators of environmental contamination. Microalgae and cyanobacteria possess the ability to degrade pesticides and produce bioactive compounds, positioning them as promising agents in eco-friendly biotechnologies. Their application could reduce reliance on synthetic agrochemicals, mitigate pollution, and support soil health, offering practical solutions for sustainable land management and environmental protection.

Acknowledgments

This research was funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan under the project: (AP23488308, 2024–2026).

References

1. Sharma B. Environmental and Socioeconomic Impacts of the Cotton Industry in Bhilwara, Rajasthan: A Comprehensive Analysis // International Journal for Research in Applied Science & Engineering Technology (IJRASET). – 2024. – T. 12, № VIII. https://doi.org/10.22214/ijraset.2024.64010
2. Sahay A. Cotton Plantations in India: The Environmental and Social Challenges // Yuridika. – 2019. – T. 34, № 3. – C. 429–442. https://doi.org/10.20473/ydk.v34i3.14944
3. Makhmadjanov S., Tokhetova L., Daurenbek N., Tagaev A., Kostakov A.K. Cotton advanced lines assessment in the Southern Region of Kazakhstan // SABRAO Journal of Breeding and Genetics. – 2023. https://doi.org/10.54910/sabrao2023.55.2.1
4. Makhmadjanov S., Tokhetova L., Daurenbek N., Tagaev A.M., Kostakov A.K. Selection of cotton varieties in a competitive nursery in the South of Kazakhstan // International Journal of Environmental Engineering and Development. – 2024. https://doi.org/10.37394/232033.2024.2.1
5. Raffa C.M., Chiampo F. Bioremediation of Agricultural Soils Polluted with Pesticides: A Review // Bioengineering. – 2021. – T. 8. – № 92. https://doi.org/10.3390/bioengineering8070092
6. Forecast: global agricultural use of pesticides 2023-2027 // Statista Research Department. – 2023, August 2. https://www.statista.com/aboutus/our-research-commitment
7. Country review of the production and use of highly hazardous pesticides in Kazakhstan // Public Foundation «Center for Sustainable Development Assistance». – 2020. – 44 p. https://ipen.org/sites/default/files/documents/final_ru_kazakhstan_hhp_country_situation_report_final_18.05.2020.pdf
8. National Report on the State of the Environment and the Use of Natural Resources of the Republic of Kazakhstan for 2018 // Ministry of Ecology, Geology, and Natural Resources.
9. Song X., Bo Y., Feng Y., Tan Y., Zhou C., Yan X., Ruan R., Xu Q., Cheng P. Potential applications for multifunctional microalgae in soil improvement // Frontiers in Environmental Science. – 2022. https://doi.org/10.3389/fenvs.2022.1035332
10. Abinandan S., Subashchandrabose S.R., Venkateswarlu K., Megharaj M. Soil microalgae and cyanobacteria: the biotechnological potential in the maintenance of soil fertility and health // Critical Reviews in Biotechnology. – 2019. – Vol. 39. – P. 981–998. https://doi.org/10.1080/07388551.2019.1654972
11. Du J., Izquierdo D., Naoum J., Ohlund L.B., Sleno L., Beisner B.E., Lavaud J., Juneau P. Pesticide responses of Arctic and temperate microalgae differ in relation to ecophysiological characteristics // Aquatic Toxicology. – 2022. – Vol. 254. – 106323. https://doi.org/10.1016/j.aquatox.2022.106323
12. Fayaz T., Rana S.S., Goyal E., Ratha S.K., Renuka N. Harnessing the potential of microalgae-based systems for mitigating pesticide pollution and its impact on their metabolism // Journal of Environmental Management. – 2024. – Vol. 357. – 120723. https://doi.org/10.1016/j.jenvman.2024.120723
13. Gollerbakh M.M., Kossinskaya E.K., Polyanskiy V.I. Manual of Freshwater Algae of the USSR. Blue-Green Algae. – Moscow: Sovetskaya Nauka, 1953.
14. Muzafarov A.M., Ergashev A.E., Khalilova S.Kh. Determinant of Blue-Green Algae in Central Asia. – Tashkent: Fangoria, 1988. – Vol. 2. – P. 406–815.
15. Guiry M.D., Guiry G.M. AlgaeBase. World-Wide Electronic Publication, National University of Ireland, Galway. – 2013. – URL: http://www.algaebase.org.
16. Hauer T., Komárek J. CyanoDB 2.0 – On-line database of cyanobacterial genera. World-wide electronic publication, University of South Bohemia & Institute of Botany AS CR. – 2022. – URL: http://www.cyanodb.cz.
17. Temraleeva A.D., Dronova S.A., Moskalenko S.V., Didovich S.V. Modern methods for isolation, purification, and cultivation of soil cyanobacteria // Journal of Microbiology. – 2016. – Vol. 85. – P. 389–399. https://doi.org/10.1134/S0026261716040159
18. Yibeltie G. The Role of Cyanobacteria on Agriculture // Journal of Natural Sciences Research. – 2018. – Vol. 8. – P. 1–5.
19. Schreiber U. Pulse-Amplitude-Modulation (PAM) fluorometry and saturation pulse method: An overview // In: Papageorgiou G.C., Govindjee (Eds.). Chlorophyll a fluorescence: Advances in photosynthesis and respiration. – Dordrecht: Springer, 2004. – P. 279–319. https://doi.org/10.1007/978-1-4020-3218-9_11
20. Codd G.A., Morrison L.F., Metcalf J.S. Cyanobacterial toxins: risk management for health protection // Toxicology and Applied Pharmacology. – 2005. – Vol. 203, No. 3. – P. 264–272. https://doi.org/10.1016/J.TAAP.2004.02.016
21. Yadav S., Rai S., Rai R., Shankar A., Singh S., Rai L.C. Cyanobacteria: Role in Agriculture, Environmental Sustainability, Biotechnological Potential and Agroecological Impact // In: Singh D., Singh H., Prabha R. (Eds.). Plant-Microbe Interactions in Agro-Ecological Perspectives. – Springer, Singapore, 2017. https://doi.org/10.1007/978-981-10-6593-4_10
22. El-Sheekh M.M., El-Kassas H.Y., Ali S.S. Microalgae-based bioremediation of refractory pollutants: an approach towards environmental sustainability // Microbial Cell Factories. – 2025. – Vol. 24. – P. 19. https://doi.org/10.1186/s12934-024-02638-0
23. Afify A.H., Ashour A.R. Using Cyanobacteria (*Nostoc* spp.) in the Biological Control of Damping-off Disease in Cotton // Journal of Agricultural Chemistry and Biotechnology. – 2023. https://doi.org/10.21608/jacb.2023.220778.1058
24. Afify A.H., Ashour A. Cyanobacteria and Fungicide as Controlling Agents for Cotton Fungal Diseases // Journal of Agricultural Chemistry and Biotechnology. – 2024. https://doi.org/10.21608/jacb.2024.260886.1073
25. Choudhary K.K., Bimal R. Distribution of nitrogen-fixing cyanobacteria (*Nostocaceae*) during rice cultivation in fertilized and unfertilized paddy fields // Nordic Journal of Botany. – 2010. – Vol. 28. – P. 100–103. https://doi.org/10.1111/J.1756-1051.2009.00486.X

26. Jiménez-Ríos L., Torrado A., Gonzalez-Pimentel J.L., Iniesta-Pallarés M., Molina-Heredia F.P., Mariscal V., Álvarez C. Emerging nitrogen-fixing cyanobacteria for sustainable cotton cultivation // Science of the Total Environment. – 2024. – 171533. https://doi.org/10.1016/j.scitotenv.2024.171533

27. Yeheyo H.A., Ealias A.M., George G., Jagannathan U.M. Bioremediation potential of microalgae for sustainable soil treatment in India: A comprehensive review on heavy metal and pesticide contaminant removal // Journal of Environmental Management. – 2024. – Vol. 363. – 121409. https://doi.org/10.1016/j.jenvman.2024.121409

28. Avila R. et al. Biodegradation of hydrophobic pesticides by microalgae: Transformation products and impact on algae biochemical methane potential // Science of the Total Environment. – 2021. – Vol. 754. – P. 142114.

29. Hersh C.M., Crumpton W.G. Atrazine tolerance of algae isolated from two agricultural streams // Environmental Toxicology and Chemistry. – 1989. – Vol. 8. – P. 327–332. https://doi.org/10.1002/ETC.5620080409

30. Qian H., Sheng G.D., Liu W., Lu Y., Liu Z., Fu Z. Inhibitory effects of atrazine on *Chlorella vulgaris* as assessed by real time polymerase chain reaction // Environmental Toxicology and Chemistry. – 2008. – Vol. 27. https://doi.org/10.1897/07-163.1

31. Carrasco J., Sabater C. Toxicity of atrazine and chlorsulfuron to algae // Toxicological & Environmental Chemistry. – 1997. – Vol. 59. – P. 89–99. https://doi.org/10.1080/02772249709358427

32. Zhang J.L., Qiao C. Novel approaches for remediation of pesticide pollutants // International Journal of Environment and Pollution. – 2002. – Vol. 18. – P. 423–433. https://doi.org/10.1504/IJEP.2002.002337

33. Sehrawat A., Phour M., Kumar R., Sindhu S.S. Bioremediation of Pesticides: An Eco-Friendly Approach for Environment Sustainability. – 2021. https://doi.org/10.1007/978-981-15-7447-4_2

34. Scott C., Pandey G., Hartley C.J., Jackson C.J., Cheesman M.J., Taylor M.C., Pandey R., Khurana J.L., Teese M.G., Coppin C.W., Weir K.M., Jain R.K., Lal R., Russell R.J., Oakeshott J.G. The enzymatic basis for pesticide bioremediation // Indian Journal of Microbiology. – 2008. – Vol. 48. – P. 65–79. https://doi.org/10.1007/s12088-008-0007-4

35. Cid Á., Prado R., Blanco C.R., Suarez Bregua P., Herrero C. Use of Microalgae as Biological Indicators of Pollution: Looking for New Relevant Cytotoxicity Endpoints. – 2012. – ID: 131840078. http://hdl.handle.net/2183/16634

References

1. Abinandan S., Subashchandrabose S.R., Venkateswarlu K., Megharaj M. Soil microalgae and cyanobacteria: the biotechnological potential in the maintenance of soil fertility and health. *Crit Rev Biotechnol*. 2019;39:981–998. https://doi.org/10.1080/07388551.2019.1654972

2. Afify A.H., Ashour A. Cyanobacteria and Fungicide as Controlling Agents for Cotton Fungal Diseases. *J Agric Chem Biotechnol*. 2024. https://doi.org/10.21608/jacb.2024.260886.1073

3. Afify A.H., Ashour A.R. Using Cyanobacteria (Nostoc spp.) in the Biological Control of Damping-off Disease in Cotton. *J Agric Chem Biotechnol*. 2023. https://doi.org/10.21608/jacb.2023.220778.1058

4. Avila R., et al. Biodegradation of hydrophobic pesticides by microalgae: Transformation products and impact on algae biochemical methane potential. *Sci Total Environ*. 2021;754:142114.

5. Carrasco J., Sabater C. Toxicity of atrazine and chlorsulfuron to algae. *Toxicol Environ Chem*. 1997;59:89–99. https://doi.org/10.1080/02772249709358427

6. Choudhary K.K., Bimal R. Distribution of nitrogen-fixing cyanobacteria (Nostocaceae) during rice cultivation in fertilized and unfertilized paddy fields. *Nord J Bot*. 2010;28:100–103. https://doi.org/10.1111/J.1756-1051.2009.00486.X

7. Cid Á., Prado R., Blanco C.R., Suarez Bregua P., Herrero C. Use of Microalgae as Biological Indicators of Pollution: Looking for New Relevant Cytotoxicity Endpoints. 2012. ID: 131840078. http://hdl.handle.net/2183/16634

8. Codd G.A., Morrison L.F., Metcalf J.S. Cyanobacterial toxins: risk management for health protection. *Toxicol Appl Pharmacol*. 2005;203(3):264–272. https://doi.org/10.1016/J.TAAP.2004.02.016

9. Du J., Izquierdo D., Naoum J., et al. Pesticide responses of Arctic and temperate microalgae differ in relation to ecophysiological characteristics. *Aquat Toxicol*. 2022;254:106323. https://doi.org/10.1016/j.aquatox.2022.106323

10. El-Sheekh M.M., El-Kassas H.Y., Ali S.S. Microalgae-based bioremediation of refractory pollutants: an approach towards environmental sustainability. *Microb Cell Fact*. 2025;24:19. https://doi.org/10.1186/s12934-024-02638-0

11. Fayaz T., Rana S.S., Goyal E., Ratha S.K., Renuka N. Harnessing the potential of microalgae-based systems for mitigating pesticide pollution and its impact on their metabolism. *J Environ Manag*. 2024;357:120723. https://doi.org/10.1016/j.jenvman.2024.120723

12. Forecast: global agricultural use of pesticides 2023–2027. *Statista Research Department*. 2023 Aug 2. https://www.statista.com/aboutus/our-research-commitment

13. Gollerbakh M.M., Kosinskaya E.K., Polyanskii V.I. Opredelitel presnovodnykh vodoroslei SSSR. Vyp. 2 [Key to freshwater algae of USSR. Vol. 2]. Moscow, Nauka Publ., 1953, 652 p. (in Russian)

14. Guiry M.D., Guiry G.M. *AlgaeBase. World-Wide Electronic Publication*, National University of Ireland, Galway. 2013. http://www.algaebase.org

15. Hauer T., Komárek J. *CyanoDB 2.0 – Online database of cyanobacterial genera*. University of South Bohemia & Institute of Botany AS CR. 2022. http://www.cyanodb.cz

16. Hersh C.M., Crumpton W.G. Atrazine tolerance of algae isolated from two agricultural streams. *Environ Toxicol Chem*. 1989;8:327–332. https://doi.org/10.1002/ETC.5620080409

17. Jiménez-Ríos L., Torrado A., Gonzalez-Pimentel J.L., et al. Emerging nitrogen-fixing cyanobacteria for sustainable cotton cultivation. *Sci Total Environ*. 2024;171533. https://doi.org/10.1016/j.scitotenv.2024.171533

18. Makhmadjanov S., Tokhetova L., Daurenbek N., Tagaev A., Kostakov A.K. Cotton advanced lines assessment in the Southern Region of Kazakhstan. *SABRAO J Breed Genet*. 2023. https://doi.org/10.54910/sabrao2023.55.2.1

19. Makhmadjanov S., Tokhetova L., Daurenbek N., Tagaev A.M., Kostakov A.K. Selection of cotton varieties in a competitive nursery in the South of Kazakhstan. *Int J Environ Eng Dev*. 2024. https://doi.org/10.37394/232033.2024.2.1

20. Ministry of Ecology, Geology, and Natural Resources. *National Report on the State of the Environment and the Use of Natural Resources of the Republic of Kazakhstan for 2018*.

21. Muzafarov A.M., Ergashev A.E., Khalilova S.Kh. Opredelitel' sine-zelenykh vodorosley Sredney Azii. [Determinant of Blue-Green Algae in Central Asia], Tashkent: Fan, 1987. – T. 1. – S. 3–405.

22. OF "Tsentr 'Sodeystvie ustoychivomu razvitiyu'". Stranovoy obzor proizvodstva i ispol'zovaniya osobo opasnykh pestitsidov v Kazakhstane [Public Foundation "Center for Sustainable Development Assistance". Country review of the production and use of highly hazardous pesticides in Kazakhstan], 2020; 44 p. https://ipen.org/sites/default/files/documents/final_ru_kazakhstan_hhp_country_situation_report_final_18.05

23. Qian H., Sheng G.D., Liu W., et al. Inhibitory effects of atrazine on *Chlorella vulgaris* as assessed by real-time polymerase chain reaction. *Environ Toxicol Chem*. 2008;27. https://doi.org/10.1897/07-163.1

24. Raffa C.M., Chiampo F. Bioremediation of Agricultural Soils Polluted with Pesticides: A Review. *Bioengineering*. 2021;8(92). https://doi.org/10.3390/bioengineering8070092

25. Sahay A. Cotton Plantations in India: The Environmental and Social Challenges. *Yuridika*. 2019;34(3):429–442. https://doi.org/10.20473/ydk.v34i3.14944

26. Schreiber U. Pulse-Amplitude-Modulation (PAM) fluorometry and saturation pulse method: An overview. In: Papageorgiou G.C., Govindjee (Eds). *Chlorophyll a fluorescence: Advances in photosynthesis and respiration*. Dordrecht: Springer; 2004. p. 279–319. https://doi.org/10.1007/978-1-4020-3218-9_11

27. Scott C., Pandey G., Hartley C.J., et al. The enzymatic basis for pesticide bioremediation. *Indian J Microbiol*. 2008;48:65–79. https://doi.org/10.1007/s12088-008-0007-4

28. Sehrawat A., Phour M., Kumar R., Sindhu S.S. *Bioremediation of Pesticides: An Eco-Friendly Approach for Environment Sustainability*. 2021. https://doi.org/10.1007/978-981-15-7447-4_2

29. Sharma B. Environmental and Socioeconomic Impacts of the Cotton Industry in Bhilwara, Rajasthan: A Comprehensive Analysis. *Int J Res Appl Sci Eng Technol (IJRASET)*. 2024;12(VIII). https://doi.org/10.22214/ijraset.2024.64010

30. Song X., Bo Y., Feng Y., et al. Potential applications for multifunctional microalgae in soil improvement. *Front Environ Sci*. 2022. https://doi.org/10.3389/fenvs.2022.1035332

31. Temraleeva A.D., Dronova S.A., Moskalenko S.V., Didovich S.V. Modern methods for isolation, purification, and cultivation of soil cyanobacteria. *J Microbiol*. 2016;85:389–399. https://doi.org/10.1134/S0026261716040159

32. Yadav S., Rai S., Rai R., et al. Cyanobacteria: Role in Agriculture, Environmental Sustainability, Biotechnological Potential and Agroecological Impact. In: Singh D., Singh H., Prabha R. (Eds). *Plant-Microbe Interactions in Agro-Ecological Perspectives*. Springer, Singapore; 2017. https://doi.org/10.1007/978-981-10-6593-4_10

33. Yeheyo H.A., Ealias A.M., George G., Jagannathan U.M. Bioremediation potential of microalgae for sustainable soil treatment in India: A comprehensive review on heavy metal and pesticide contaminant removal. *J Environ Manag*. 2024;363:121409. https://doi.org/10.1016/j.jenvman.2024.121409

34. Yibeltie G. The Role of Cyanobacteria on Agriculture. *J Nat Sci Res*. 2018;8:1–5.

35. Zhang J.L., Qiao C. Novel approaches for remediation of pesticide pollutants. *Int J Environ Pollut*. 2002;18:423–433. https://doi.org/10.1504/IJEP.2002.002337

Авторлар туралы мәлімет:

Акмуханова Нурзия Рахмедиевна – к.б.н., и.о. профессора кафедры биотехнологии, КазНУ, 050040, Алматы, Казахстан. ORCID ID: https://orcid.org/0000-0002-9274-807X, akmukhanova.nurziya@gmail.com

Сейілбек Сандугаш Нұрланкызы – PhD докторант 3 курса специальности «Биотехнология» кафедры биотехнологии Казахского национального университета имени аль-Фараби Алматы, Казахстан, https://orcid.org/0000-0003-4897-12046, sseilbek1@gmail.com

Бақытжан Рамина Әміргалиқызы – магистрант 2 курса специальности «Биотехнология» кафедры биотехнологии Казахского национального университета имени аль-Фараби Алматы, Казахстан, ramina.baytzhan@mail.ru 6 ORCID ID: https://orcid.org/0009-0002-3262-681X

Домаш Гүлжайна Серікқызы – магистрант 2 курса специальности «Биотехнология» кафедры биотехнологии Казахского национального университета имени аль-Фараби Алматы, Казахстан, domashg28@mail.ru, https://orcid.org/0009-0003-0035-2460

Амин Сукрон – студент 3 курса бакалавриата по специальности «Биотехнология» кафедры биотехнологии Казахского национального университета имени аль-Фараби, Алматы, Казахстан. sukronamin1612@gmail.com, ORCID ID: https://orcid.org/0009-0004-9413-3492

Information about authors:

Akmukhanova Nurziya (corresponding author) – Candidate of Biological Sciences, Acting Professor of the Department of Biotechnology, Al-Farabi Kazakh National University, 050040, Almaty, Kazakhstan. ORCID ID: https://orcid.org/0000-0002-9274-807X, akmukhanova.nurziya@gmail.com

Seilbek Sandugash – 3rd-year PhD student in "Biotechnology" at the Department of Biotechnology, Al-Farabi Kazakh National University, Almaty, Kazakhstan. ORCID ID: https://orcid.org/0000-0003-4897-12046, sseilbek1@gmail.com

Bakytzhan Ramina – 2nd-year master's student in "Biotechnology" at the Department of Biotechnology, Al-Farabi Kazakh National University, Almaty, Kazakhstan, ramina.baytzhan@mail.ru, ORCID ID: https://orcid.org/0009-0002-3262-681X

Domash Gulzhaina – 2nd-year master's student in "Biotechnology" at the Department of Biotechnology, Al-Farabi Kazakh National University, Almaty, Kazakhstan, domashg28@mail.ru, ORCID ID: https://orcid.org/0009-0003-0035-2460

Amin Sukron – 3rd-year bachelor's student in the Biotechnology program at the Department of Biotechnology, al-Farabi Kazakh National University, Almaty, Kazakhstan. sukronamin1612@gmail.com, ORCID ID: https://orcid.org/0009-0004-9413-3492

Received January 18, 2025
Re-uploaded April 2, 2025
Accepted May 20, 2025