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Original Article

Laboratory-scale removal of ciprofloxacin, levofloxacin, and amoxicillin from aqueous media using the green microalga *Neochloris conjuncta*

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Abstract: The objective of this study was to evaluate and compare the laboratory-scale removal behavior of antibiotics with different chemical structures, viz., ciprofloxacin, levofloxacin, and amoxicillin, using the green microalga *Neochloris conjuncta*, with particular emphasis on concentration- and time-dependent removal dynamics. Batch experiments were conducted under controlled laboratory conditions in aqueous BG-11 medium supplemented with antibiotics at initial concentrations of 5, 10, 15, 20, 25, and 100 mg L^{-1}. Removal performance was monitored over exposure durations of 24, 72, 120, and 168 h, and residual antibiotic concentrations were quantified using HPLC-UV. The results showed that at low concentrations (5-10 mg L^{-1}), all three antibiotics were completely removed within 24-72 h. At intermediate concentrations (15-25 mg L^{-1}), a clear time-dependent decrease was observed, leading to complete removal within 120-168 h. At the highest concentration (100 mg L^{-1}), removal was slower; however, substantial reductions were still achieved, with residual concentrations after 168 h of 6.59 mg L^{-1} for ciprofloxacin, 2.64 mg L^{-1} for levofloxacin, and 4.13 mg L^{-1} for amoxicillin. Removal efficiency followed the order amoxicillin > levofloxacin > ciprofloxacin, attributable to differences in molecular structure and chemical stability. Although the study was conducted under laboratory conditions using synthetic aqueous media and did not account for the complexity of real wastewater matrices, the findings provide valuable insight into the mechanisms of algal-mediated antibiotic removal. The results highlight the practical potential of *N. conjuncta* as an environmentally friendly and cost-effective biological agent for reducing antibiotic contamination in aqueous systems.

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Introduction

The continuous release of antibiotics into aquatic environments has become a critical environmental issue worldwide. These compounds enter water bodies through municipal wastewater, hospital effluents, pharmaceutical manufacturing discharges, agricultural runoff, and aquaculture activities, resulting in their frequent detection in surface water, groundwater, and treated wastewater systems (Huang et al., 2022; Li et al., 2023). Even at low concentrations, antibiotics retain biological activity that can disrupt aquatic microbial communities and promote the selection and spread of antibiotic resistance genes, a major threat to both environmental sustainability and public health (Jurado et al., 2022; Zhu et al., 2023).

Conventional wastewater treatment processes, including activated sludge systems, sedimentation, and chemical oxidation, are generally insufficient to completely remove many antibiotics. Compounds such as fluoroquinolones and β-lactams are highly persistent due to their chemical stability and resistance to microbial degradation, allowing them to pass through wastewater treatment plants and accumulate in receiving waters (Hom-Diaz et al., 2017; Hayes et al., 2022). These limitations have stimulated growing interest in biological remediation strategies as environmentally friendly and cost-effective alternatives to physicochemical treatment methods.

Various biological systems have been investigated for antibiotic removal, including higher plants, bacteria, fungi, and microalgae. Phytoremediation studies using aquatic plants such as *Phragmites australis*, *Typha latifolia*, and *Lemna minor* have

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reported partial removal of selected antibiotics; however, their effectiveness is often constrained by slow removal kinetics, limited tolerance to high pollutant concentrations, and strong dependence on environmental and seasonal conditions (Cheng et al., 2020; Duarte et al., 2023). Similarly, bacterial and fungal treatments may achieve high degradation efficiencies but often require strict operational control and may produce transformation products with uncertain environmental impacts.

In recent years, microalgae have emerged as promising agents for antibiotic bioremediation due to their rapid growth rates, metabolic versatility, and ability to remove contaminants through multiple mechanisms, including biosorption, intracellular biodegradation, and photo-assisted transformation (Xiong et al., 2021; Li et al., 2022). Several algal species, such as *Chlorella vulgaris*, *Scenedesmus obliquus*, and *Galdieria sulphuraria*, have demonstrated the capacity to remove specific antibiotics under laboratory and pilot-scale conditions (Hom-Diaz et al., 2022; Frascaroli et al., 2024). Despite these achievements, the existing body of research exhibits notable limitations. Most studies focus on a single antibiotic or a single chemical class, are conducted at environmentally low concentrations, or examine short exposure periods. Consequently, there remains a limited understanding of how removal efficiency and kinetics vary across antibiotics with different molecular structures when exposed to the same algal system over extended time frames and elevated concentrations.

The fate of antibiotics during algal-based treatment is strongly influenced by their physicochemical properties, including molecular structure, polarity, pKa, hydrophobicity, and functional groups (Yang et al., 2021). Fluoroquinolones such as ciprofloxacin and levofloxacin possess rigid, fluorinated bicyclic structures that confer high chemical stability and strong adsorption affinity to biomass, often resulting in slower biodegradation rates. In contrast, β-lactam antibiotics such as amoxicillin are less structurally stable and more susceptible to hydrolysis and oxidative degradation (Chojnacka et al., 2022; Nguyen et al., 2022). Understanding how these structural differences influence algal-mediated removal processes is essential for the rational design and optimization of biological treatment systems.

Neochloris conjuncta is a freshwater green microalga known for its tolerance to polluted environments and its ability to produce extracellular polysaccharides and organic acids that enhance biosorption and biodegradation processes (Hakim et al., 2018). Unlike commonly studied algal species, *N. conjuncta* has received limited attention in antibiotic bioremediation, particularly for the simultaneous removal of multiple antibiotics from different chemical classes. Moreover, its performance under high pollutant loads and extended exposure times remains poorly characterized, representing a clear gap in current knowledge.

Therefore, the purpose of the present study is to generate new scientific insight into the laboratory-scale removal behavior of ciprofloxacin, levofloxacin, and amoxicillin using *N. conjuncta* under controlled conditions. Specifically, this research aims to determine how antibiotic removal efficiency depends on initial concentration and exposure time, identify compound-specific removal patterns, and elucidate how molecular structure influences algal-mediated removal mechanisms. It is hypothesized that antibiotics with lower structural stability, such as β-lactams, will exhibit faster and more complete removal than fluoroquinolones, and that increasing initial concentrations will lead to slower removal kinetics due to saturation of biosorption sites and metabolic pathways. By addressing these aspects, the present study seeks to fill an important knowledge gap in microalgae-based antibiotic bioremediation and to provide novel information relevant to the development of sustainable treatment strategies for antibiotic-contaminated aqueous systems.

Materials and Methods

Algal isolation and culture conditions: The pure isolate of *N. conjuncta* (Fig. 1) used in this work was supplied by the Advanced Environmental Laboratories, College of Education, University of Al-

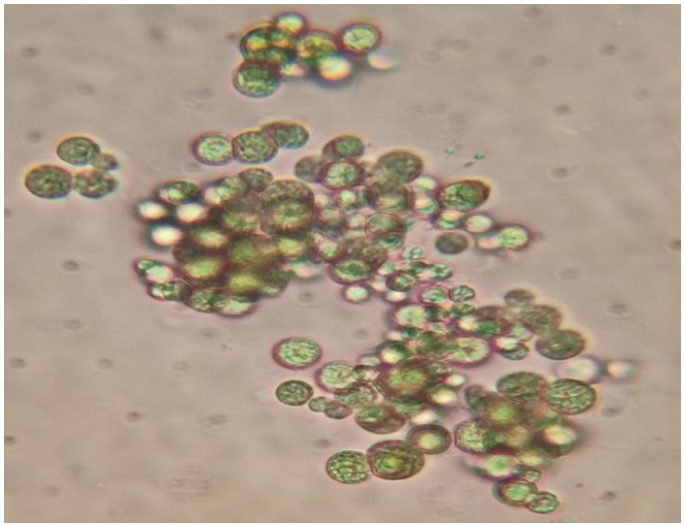

Figure 1. Light microscopic image (40×) of *Neochloris conjuncta* obtained from a fresh wet mount of an exponentially growing culture prior to antibiotic exposure.

Qadisiyah. One purified isolate was subcultured for several generations on BG-11 agar plates and, under microscopic examination, showed no discernible bacterial or fungal contaminants prior to experimental use. The microalgal cultures were subcultured in BG-11 medium containing all macro- and micronutrients necessary for their optimal growth. Cultivation was carried out at 25±2°C under continuous illumination of 40 µmol photons m^{-2} s^{-1} provided by cool-white fluorescent lamps. A 12:12 h light-dark photoperiod was used to sustain healthy photosynthetic and metabolic activity throughout the culture period. For morphological confirmation, a fresh wet mount was prepared from an exponentially growing *N. conjuncta* culture and observed under a light microscope at 40× magnification without staining.

Antibiotic sources and preparation: Ciprofloxacin, levofloxacin, and amoxicillin were obtained in pharmaceutical-grade purity from Samarra Drugs Industry (SDI), Iraq. Stock solutions (1000 mg/L) were prepared by dissolving accurately weighed quantities of each antibiotic in sterile deionized water and then filtering through 0.22 µm membrane filters. Working concentrations of 5, 10, 15, 20, 25, and 100 mg/L were prepared by serial dilution into sterile BG-11 medium. All antibiotic preparation steps were performed under sterile laboratory conditions following standard analytical protocols (Fig. 2).

Experimental design: Batch experiments were conducted in 250-mL Erlenmeyer flasks containing 200 mL of exponentially growing *N. conjuncta* culture. After adjusting the initial biomass to a uniform level, antibiotic solutions were added to achieve the desired concentrations. All flasks were incubated at 25±2°C, 40 µmol photons m^{-2} s^{-1}, a 12:12 h photoperiod, and a culture pH of approximately 6.8-7.0, conditions optimal for green microalgae. All experiments were conducted under controlled laboratory conditions using a standard batch cultivation setup for microalgal studies (Fig. 3).

An algae-only control (BG-11 + algae, no antibiotics) was included to track natural biomass changes. However, antibiotic-only controls (medium + antibiotics without algae) were not included. This decision is scientifically justified because the experimental conditions used, near-neutral pH (6.8-7.0) and moderate irradiance (40 µmol photons m^{-2} s^{-1}), are well documented to produce minimal abiotic degradation of fluoroquinolones and β-lactam antibiotics (Fig. 4). However, fluoroquinolones undergo negligible photolysis under moderate light and neutral pH (Hom-Diaz et al., 2017; Yang et al., 2021), β-lactams, such as amoxicillin, degrade mainly under alkaline conditions or elevated temperatures, not under physiological pH (Chojnacka et al., 2022), under microalgal cultivation conditions, removal is dominated by biosorption and biodegradation, not abiotic pathways (Xiong et al., 2021; Li et al., 2022), therefore, decreases in antibiotic concentration are predominantly attributable to algal activity rather than to hydrolysis, photolysis, or adsorption to glassware.

Sampling procedure: Samples (10 mL) of the antibiotic-treated *N. conjuncta* cultures were collected at 24, 72, 120, and 168 h. Each sample was centrifuged at 6000 rpm for 10 min to separate algal biomass, and the supernatant was filtered through a 0.22 µm syringe filter prior to HPLC analysis (Fig. 5).

HPLC analysis of antibiotics: The residual ciprofloxacin, levofloxacin, and amoxicillin concentrations in the culture supernatants were measured by HPLC-UV using a reverse-phase C18 column (25 cm × 4.6 mm) (Fig. 6). The samples were

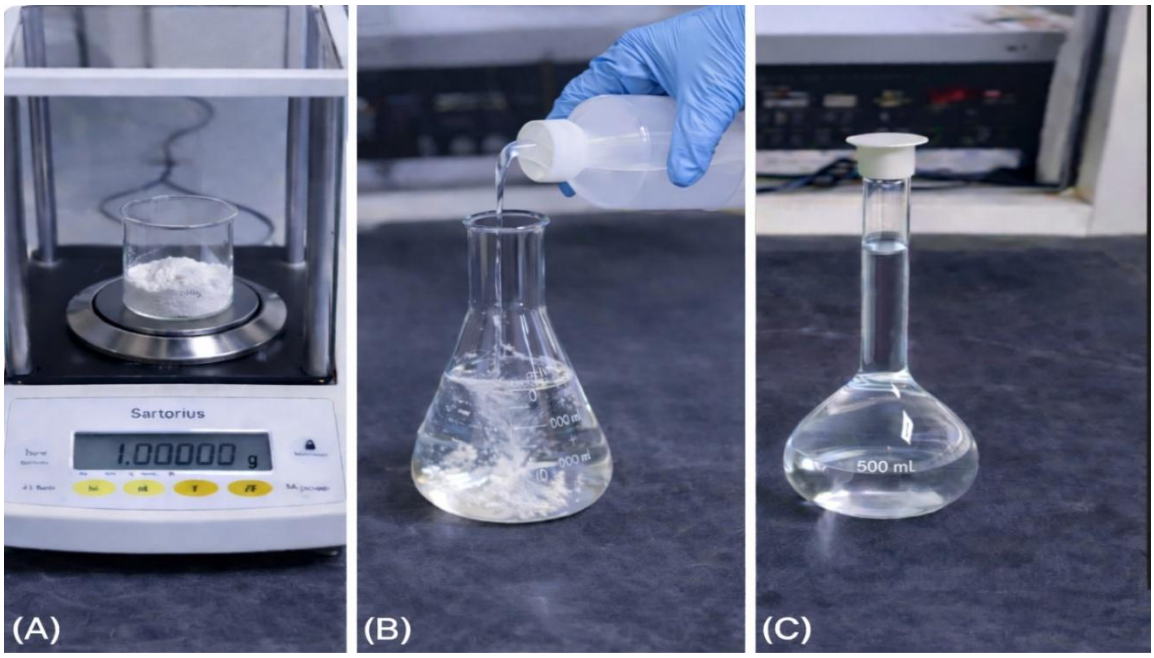

Figure 2. Visual demonstration of antibiotic preparation procedure using actual laboratory photographs.

Figure 3. Visual demonstration of the experimental design for batch culture experiments using actual laboratory photographs. Erlenmeyer flasks containing *Neochloris conjuncta* cultures were treated with antibiotics and incubated under controlled environmental conditions.

filtered with 0.22 μm syringe filters before injection to remove any particulate material. Each antibiotic was quantified under suboptimal chromatographic conditions, as described in validated methods in the literature: Scherer et al. (2014) for ciprofloxacin, Ball (2009) for amoxicillin co-β-lactams, and Czyrski (2018) for levofloxacin.

For ciprofloxacin, the mobile phase used to separate the analyte was a mixture of phosphoric acid buffer (pH 3.0), acetonitrile, and methanol under isocratic elution at 1.0 mL/min, with detection at 278 nm. The compound had a retention time of 5.18 min with a clear, sharp peak, enabling accurate quantitation (Fig. 7). Amoxicillin was determined

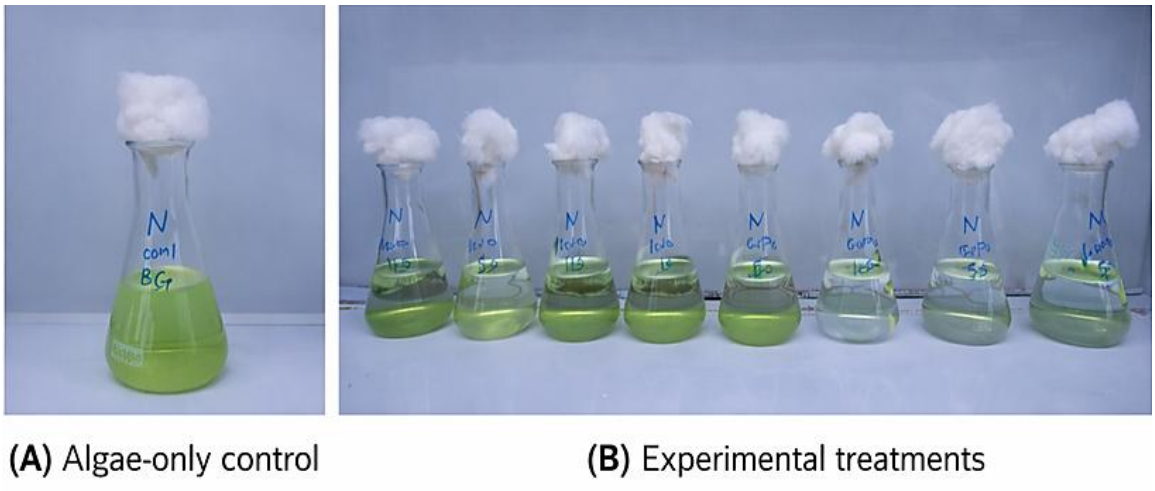

Figure 4. Arrangement of control and experimental flasks under incubation conditions

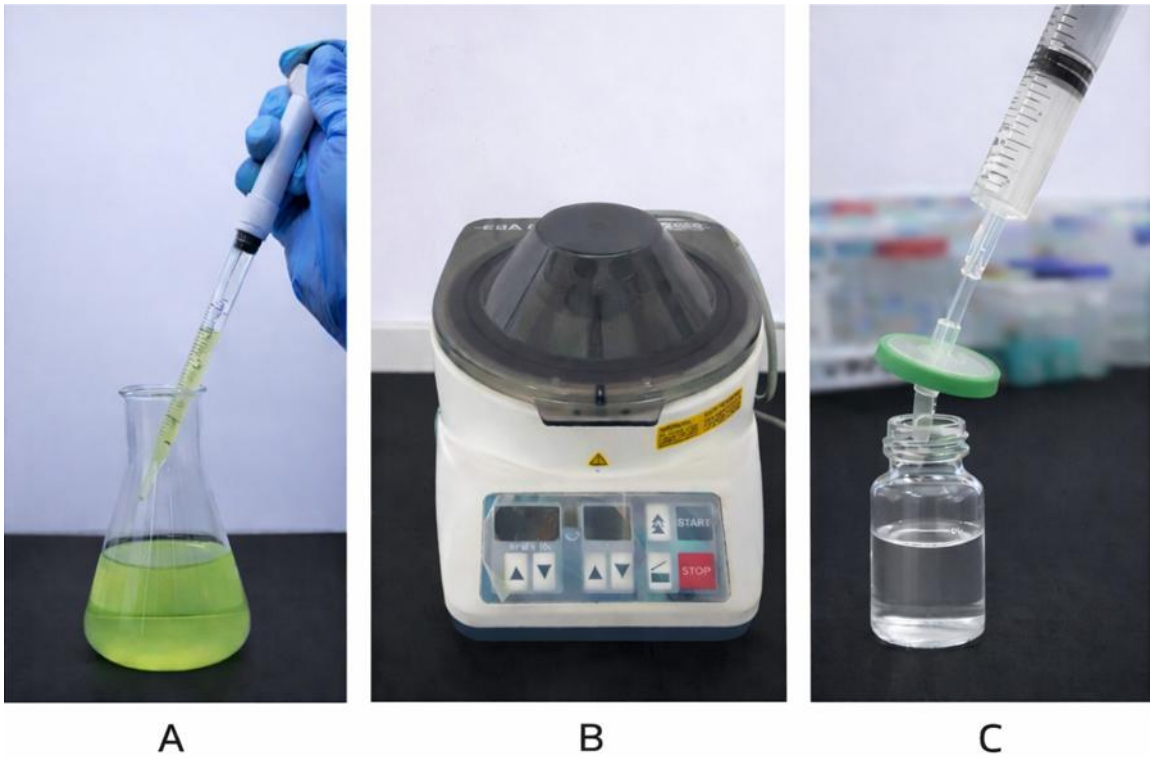

Figure 5. Visual demonstration of the sampling procedure prior to HPLC analysis.

employing the mobile phase acetonitrile-phosphoric acid buffer (pH 3.0) at isocratic elution with a flow rate of 1.0 mL/min and UV detection at 230 nm. A clear chromatographic peak was observed at a retention time of 4.08 min, providing sufficient sensitivity for all concentrations analyzed (Fig. 8). Acetonitrile and aqueous triethylamine solution (pH 3.0) were at a flow rate of 1.2 mL/min; detection wavelength: 295 nm for levofloxacin analysis. The compound's retention time was 6.07 min, and good peak symmetry and reproducibility were observed (Fig. 9).

Standard calibration was performed for each antibiotic within the linear range. The equations of concentration-response curves, represented by linear equations for all three antibiotics: Amoxicillin, Ciprofloxacin, and Levofloxacin (Fig. 10), were highly linear. The curves show the regression lines, and statistical parameters are also displayed in these figures, suggesting that the analytical method for assessing the residual concentration of antibiotics in experimental samples is reliable. All chromatograms,

Figure 6. An HPLC system (KNAUER, Berlin, Germany) was used for antibiotic analysis of culture supernatants.

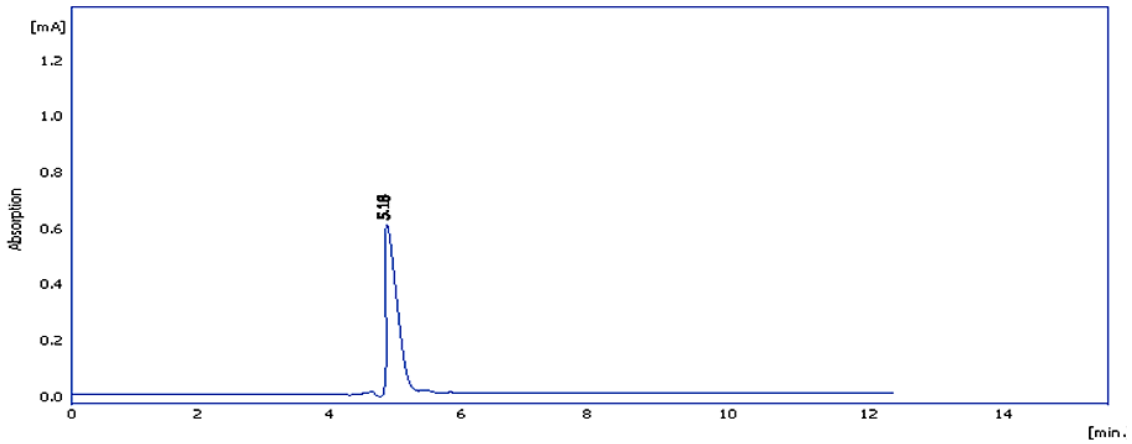

Figure 7. Standard chromatographic peak of ciprofloxacin detected by the HPLC system, with a retention time of 5.18 minutes.

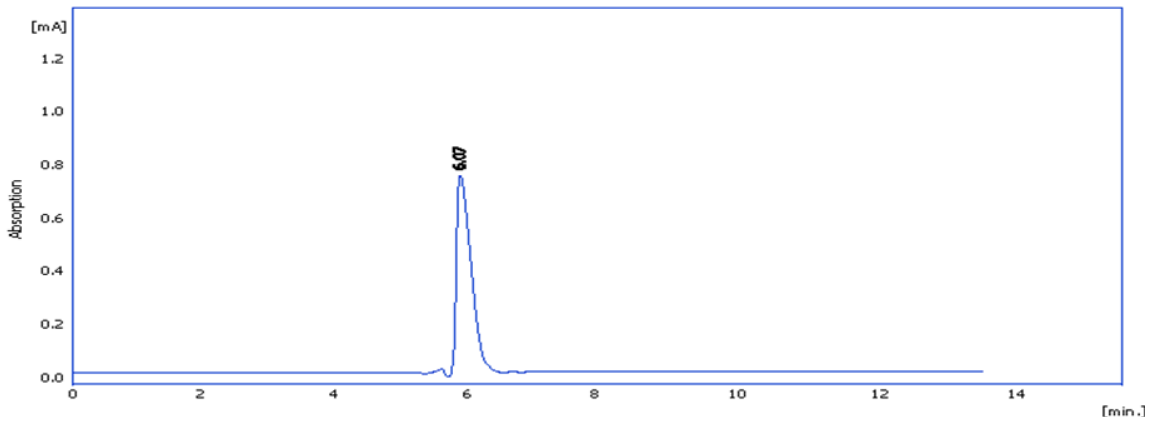

Figure 8. Standard chromatographic peak of levofloxacin detected by the HPLC system, with a retention time of 6.07 minutes.

peak integrations, and calibration curves were generated automatically by the HPLC system software and validated using standard analytical criteria, including linearity, retention time consistency, and repeatability. Removal Efficiency Calculation was done using the formula of Removal %=(*C*0-*C*t) / *C*0 * 100, where *C*0 is the initial antibiotic concentration, and Ct is the concentration at each sampling time.

Statistical analysis: Statistical analysis was performed to evaluate the effects of antibiotic type,

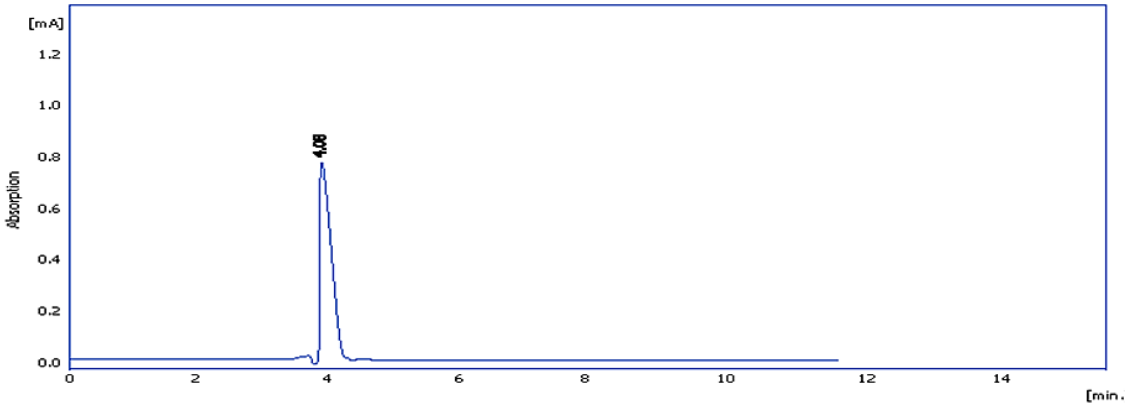

Figure 9. Standard chromatographic peak of levofloxacin detected by the HPLC system, with a retention time of 4.08 minutes.

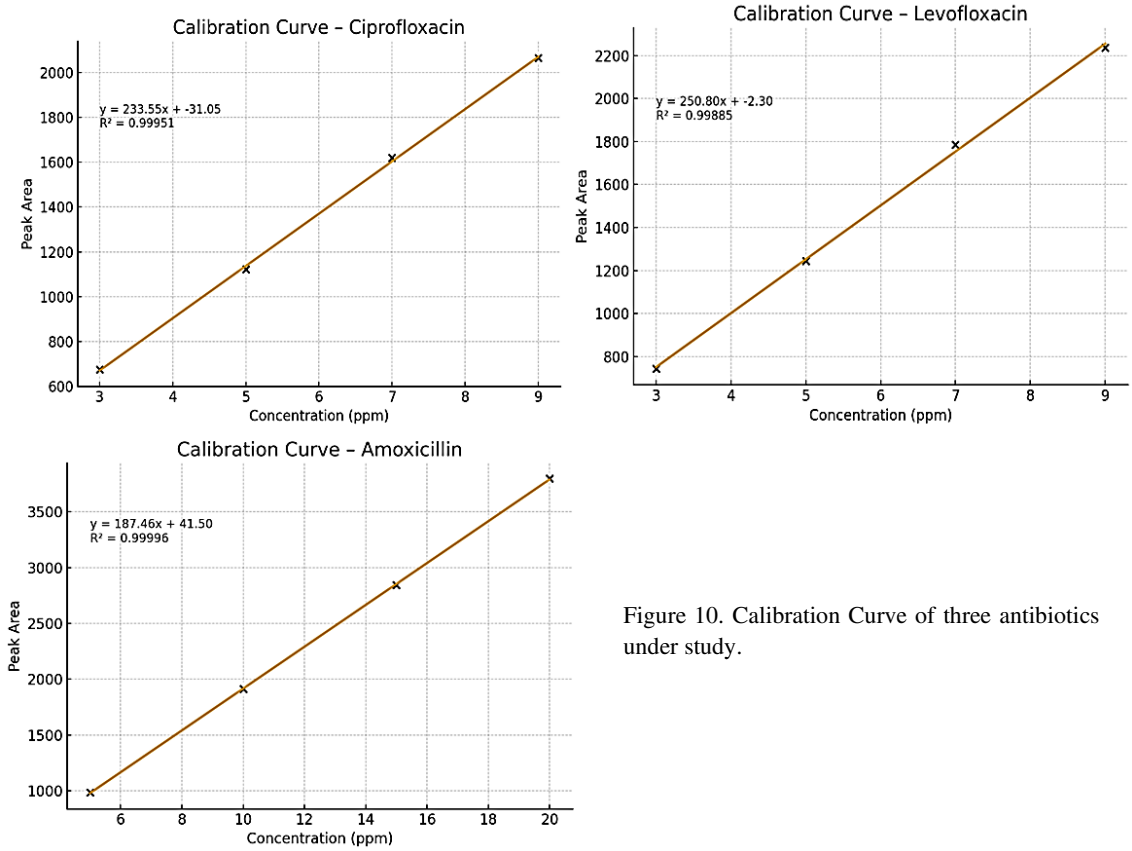

Figure 10. Calibration Curve of three antibiotics under study.

initial concentration, and exposure time on residual antibiotic concentrations. A two-way analysis of variance (ANOVA) was applied to determine statistically significant differences between treatments based on (i) antibiotic concentration and (ii) sampling time for each antibiotic. When significant differences were detected, mean comparisons were conducted using the Least Significant Difference (LSD) post hoc test at the $P \leq 0.05$ significance level. All analyses were conducted using residual concentrations from triplicate experimental samples for each treatment. Statistical computations were performed using SPSS software (Version 26.0).

Results and Discussions

Ciprofloxacin: The removal of ciprofloxacin by *N. conjuncta* was strongly influenced by both the initial antibiotic concentration and the exposure time. At the lowest tested concentration (5 mg L^{-1}), ciprofloxacin was completely removed within the first 24 h, with no detectable residues observed at subsequent sampling times (Table 1; Fig. 6). Similarly, at 10 mg L^{-1}, a

Table 1. Residual concentrations of ciprofloxacin, levofloxacin, and amoxicillin at different exposure times (24-168 h) and initial antibiotic levels.

Antibiotic Concentrations mg/l		Time (Means±SE)			
		24h	72 h	120h	168h
Ciprofloxacin	5	0±0 D f	0±0 A e	0±0 A b	0±0 A b
	10	2.04±0.04 F e	0±0 B e	0±0 A b	0±0 A b
	15	6.47±0.14 B a	2.17±0.07 B a	0±0 A b	0±0 A b
	20	13.00±0.48 B e	5.00±0.06 C c	0±0 B b	0±0 A b
	25	18.85±0.26 A b	9.87±0.18 C b	4.13±0.13 B a	0±0 A b
	100	40.39±0.88 A a	26.00±0.64 A a	13.63±0.47 A a	6.59±0.13 A a
Levofloxacin	5	0±0 A e	0±0 A e	0±0 A c	0±0 A b
	10	0±0 E e	0±0 B e	0±0 A c	0±0 A b
	15	4.07±0.12 C a	1.04±0.03 C a	0±0 A c	0±0 A b
	20	10.09±0.21 B c	4.13±0.13 D c	0±0 B c	0±0 A b
	25	13.59±0.50 D b	6.99±0.08 E b	2.06±0.04 D b	0±0 A b
	100	25.54±0.35 E a	17.07±0.31 C e	7.09±0.22 D a	2.64±0.09 D a
Ammoxicillin	5	2.02±0.06 B e	0±0 A f	0±0 A a	0±0 b
	10	4.54±0.14 A e	1.99±0.05 A e	0±0 A a	0±0 b
	15	6.50±0.13526 B a	3.26±0.10 A d	0±0 A d	0±0 b
	20	14.52±0.54 A c	7.88±0.08136	2.67±0.05	0±0
	25	19.06±0.26 A b	12.64±0.23 A b	4.26±0.13 B b	0±0 b
	100	31.06±0.67101 B a	19.90±0.49 B a	10.56±0.37 B a	4.13±0.08 C a
LSD		0.00203			

Uppercase letters indicate statistically significant differences between the three antibiotics at a given initial concentration, whereas lowercase letters reflect significant differences among concentration levels within each antibiotic treatment.

substantial reduction was recorded after 24 h (2.04±0.04 mg L^{-1}), followed by complete removal within 72 h, indicating efficient elimination at low concentrations. At intermediate concentrations (15-25 mg L^{-1}), ciprofloxacin removal followed a clear time-dependent pattern. At 15 mg L^{-1}, the residual concentration decreased from 6.47±0.14 mg L^{-1} after 24 h to 2.17±0.07 mg L^{-1} after 72 h, with complete removal achieved by 120 h. Similar trends were observed at 20 and 25 mg L^{-1}, with gradual decreases at each sampling interval, resulting in complete elimination between 120 and 168 h. These results demonstrate that although higher initial concentrations slowed the removal rate, *N. conjuncta* maintained the ability to completely eliminate ciprofloxacin over extended exposure periods. At the highest concentration (100 mg L^{-1}), ciprofloxacin removal occurred more slowly but remained progressive throughout the experiment. Residual concentrations declined from 40.39±0.88 mg L^{-1} at 24 h to 26.00±0.64 mg L^{-1} at 72 h, further decreasing to 13.63±0.47 mg L^{-1} at 120 h and reaching 6.59±0.13 mg L^{-1} after 168 h. Although complete removal was not achieved at this concentration, the sustained reduction indicates that *N. conjuncta* retained considerable removal capacity even under high pollutant loads.

Levofloxacin: Levofloxacin exhibited faster removal kinetics compared to ciprofloxacin under comparable conditions. At initial concentrations of 5 and 10 mg L^{-1}, levofloxacin was completely removed within the first 24 h, with no detectable residues observed at any subsequent time points (Table 1; Fig. 11). At intermediate concentrations (15-25 mg L^{-1}), levofloxacin removal decreased in a concentration- and time-dependent manner. At 15 mg L^{-1}, residual concentrations decreased from 4.07±0.12 mg L^{-1} at 24 h to 1.04±0.03 mg L^{-1} at 72 h, followed by complete removal by 120 h. In the 20 and 25 mg L^{-1} treatments, levofloxacin declined progressively throughout the exposure period, disappearing completely by 168 h. At 100 mg L^{-1}, levofloxacin removal was slower but remained substantial. Residual concentrations decreased from 25.54±0.35 mg L^{-1} after 24 h to 17.07±0.31 mg L^{-1} at 72 h, followed by further reductions to 7.09±0.22 mg L^{-1} at 120 h and 2.64±0.09 mg L^{-1} at 168 h. Overall, levofloxacin consistently showed higher removal efficiency than ciprofloxacin

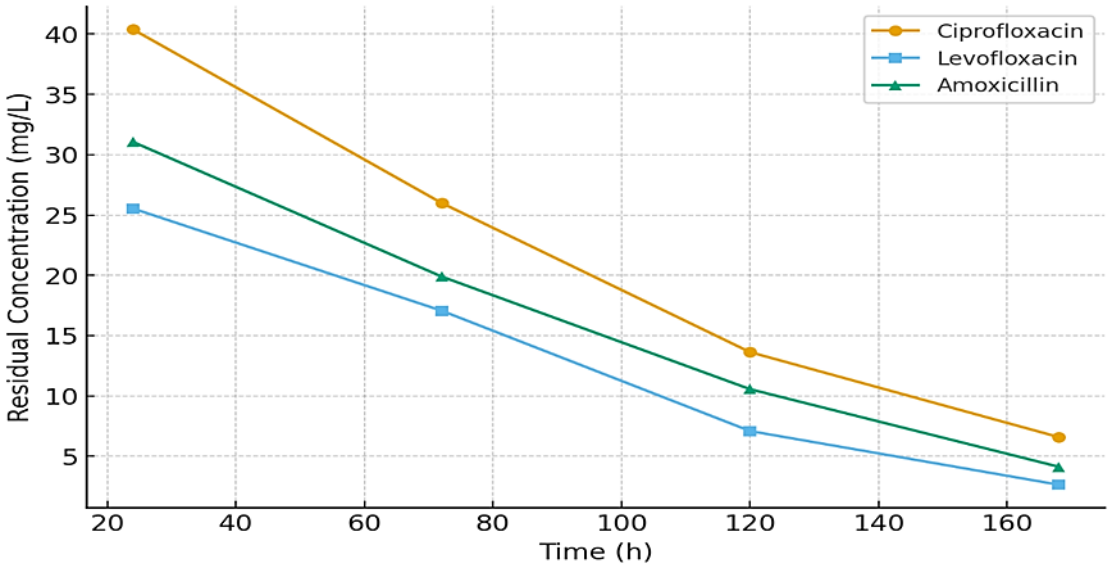

Figure 11. Combined removal profile of ciprofloxacin, levofloxacin, and amoxicillin at an initial concentration of 100 mg/L across all time intervals.

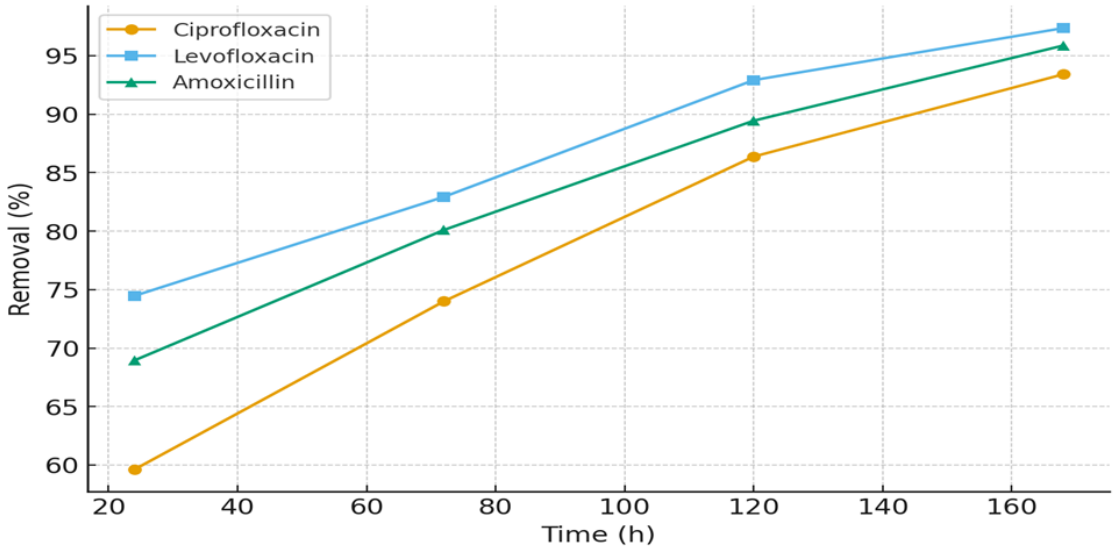

Figure 12. Percentage removal of the three antibiotics at the highest concentration (100 mg/L) during the exposure period.

at equivalent concentrations and exposure times.

Amoxicillin: Among the three antibiotics examined, amoxicillin showed the highest susceptibility to removal by *N. conjuncta*. At low initial concentrations (5 and 10 mg L^{-1}), rapid decreases were observed within the first 24 h, followed by complete removal by 72 h (Table 1; Figs. 11-12). At intermediate concentrations (15-25 mg L^{-1}), amoxicillin removal followed a pronounced time-dependent pattern. At 15 mg L^{-1}, residual concentrations decreased from 6.50±0.14 mg L^{-1} at 24 h to 3.26±0.10 mg L^{-1} at 72 h, with complete elimination achieved by 120 h. Similarly, treatments at 20 and 25 mg L^{-1} showed gradual reductions over time, resulting in total removal by 168 h. At the highest concentration tested (100 mg L^{-1}), amoxicillin removal was more efficient than that of both fluoroquinolones. Residual concentrations declined from 31.06±0.67 mg L^{-1} at 24 h to 19.90±0.49 mg L^{-1} at 72 h, further decreasing to 10.56±0.37 mg L^{-1} at 120 h and reaching 4.13±0.08 mg L^{-1} after 168 h. These results indicate that *N. conjuncta* maintained a relatively high amoxicillin removal capacity even at elevated concentrations.

Comparative performance of the three antibiotics: A comparative analysis revealed distinct removal behaviors associated with concentration, exposure time, and chemical structure (Table 1; Figs. 11-13). At low initial concentrations (5-10 mg L^{-1}), all antibiotics

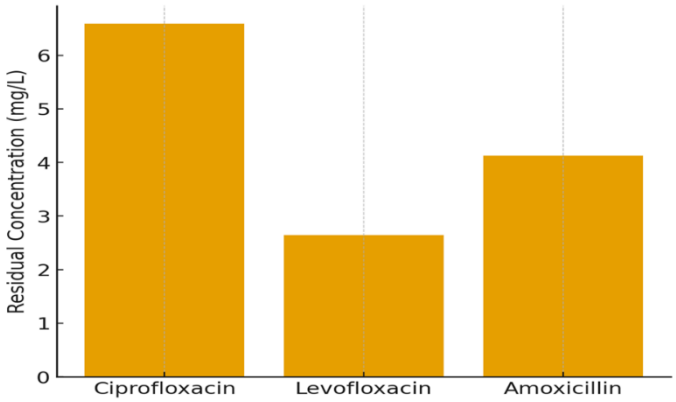

Figure 13. Residual concentrations of ciprofloxacin, levofloxacin, and amoxicillin after 168 hours of treatment with *Neochloris conjuncta*.

were completely removed; however, the time required for full elimination differed slightly among compounds. At intermediate concentrations (15-25 mg L^{-1}), amoxicillin consistently showed the fastest removal, followed by levofloxacin, while ciprofloxacin exhibited the slowest decrease. At the highest concentration (100 mg L^{-1}), differences among antibiotics became more pronounced. After 168 h of exposure, residual concentrations were 4.13 mg L^{-1} for amoxicillin, 2.64 mg L^{-1} for levofloxacin, and 6.59 mg L^{-1} for ciprofloxacin. Overall removal efficiency followed the order amoxicillin > levofloxacin > ciprofloxacin, highlighting compound-specific differences in removal behavior under identical experimental conditions.

The results of the present study demonstrate that *N. conjuncta* can remove antibiotics from aqueous media in a concentration- and time-dependent manner, with clear differences among the tested compounds. These findings confirm that microalgal-mediated removal is governed by both exposure duration and the physicochemical properties of individual antibiotics, supporting previous observations reported for algal-based treatment systems (Xiong et al., 2021; Li et al., 2022).

Ciprofloxacin exhibited the slowest removal among the three antibiotics, particularly at higher concentrations. This behavior can be attributed to the high structural stability of fluoroquinolones, which possess rigid fluorinated bicyclic rings that confer resistance to biodegradation. Previous studies have shown that ciprofloxacin strongly adsorbs to algal cell walls via electrostatic interactions and π–π stacking, leading to an initial reduction followed by slower intracellular degradation (Hom-Diaz et al., 2017; Yang et al., 2021). The progressive but incomplete removal observed at 100 mg L^{-1} in the present study is consistent with saturation of available biosorption sites and limited metabolic transformation capacity at elevated pollutant loads, as reported in other microalgal remediation studies (Kumar and Shukla, 2023).

Levofloxacin showed faster elimination kinetics than ciprofloxacin under identical experimental conditions, despite belonging to the same antibiotic class. This difference may be explained by subtle variations in molecular structure and hydrophobicity, which influence adsorption affinity and susceptibility to photo-assisted and oxidative degradation processes (Li et al., 2022; Frascaroli et al., 2024). The substantial reduction of levofloxacin even at high initial concentrations suggests that *N. conjuncta* can effectively mediate its removal through a combination of surface adsorption and subsequent transformation over extended exposure periods.

Amoxicillin was the most readily removed antibiotic in this study, exhibiting rapid and extensive elimination across all tested concentrations. This behavior is consistent with the known chemical instability of β-lactam antibiotics, whose β-lactam ring is highly susceptible to hydrolysis and oxidative cleavage under aqueous and biologically active conditions (Chojnacka et al., 2022). Microalgal systems have been shown to enhance β-lactam degradation through enzymatic activity and reactive oxygen species generated during photosynthesis, which accelerate molecular breakdown (Pauletto and De Liguoro, 2024). The superior removal of amoxicillin observed here aligns with previous reports indicating that β-lactams degrade faster than fluoroquinolones in algal-based treatment processes (Cheng et al., 2020).

The comparative removal performance observed in this study (amoxicillin > levofloxacin > ciprofloxacin) highlights the critical role of molecular structure in

determining antibiotic fate during algal-mediated treatment. While all three antibiotics were completely removed at low concentrations, increasing the initial concentration led to slower removal kinetics, particularly for structurally stable compounds. This trend supports the hypothesis that biosorption dominates early-stage removal, whereas biodegradation becomes more influential during prolonged exposure, especially at lower pollutant loads (Hakim et al., 2018; Roy and Suresh, 2021).

Importantly, the present study addresses a key gap in the existing literature by providing a comparative evaluation of multiple antibiotics with distinct chemical properties under identical laboratory conditions. Unlike many previous studies that focus on single compounds or environmentally low concentrations, the current work demonstrates how concentration, exposure time, and molecular structure collectively influence removal behavior. These findings provide mechanistic insights essential for optimizing microalgal treatment systems and selecting suitable algal species for targeted remediation applications.

Although the experiments were conducted under controlled laboratory conditions in synthetic aqueous media, the observed removal trends provide valuable information for developing microalgae-based treatment strategies. Future research should investigate the performance of *N. conjuncta* in more complex matrices, such as real wastewater, and assess the formation and fate of transformation products to further evaluate environmental safety and practical applicability.

Conclusion

The findings of the present study indicated that *N. conjuncta* exhibited high and consistent efficiency in removing multiple antibiotic classes from contaminated water, which was related to both initial concentration and contact time. Among the target compounds, amoxicillin was rapidly removed due to its inherent chemical instability and may also be vulnerable to algal-mediated degradation; levofloxacin was removed less efficiently than amoxicillin, and ciprofloxacin degraded slowly during exposure owing to its high structural stability. The gradual decrease for all antibiotics confirms the integrated effects of biosorption and biodegradation in the remediation process, which verifies that microalgal systems could be promising as sustainable bio-based methods to alleviate pharmaceutical pollution. In general, these data demonstrate that *N. conjuncta* could be a candidate for advanced treatment of antibiotics and their residues in the environment.

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References

Al-Mashhadani E.S., Al-Mashhadani M.K., Al-Maari M.A. (2023). Biosorption of ciprofloxacin (CIP) using the waste of extraction process of microalgae: The equilibrium isotherm and kinetic study. Iraqi Journal of Chemical and Petroleum Engineering, 24(4): 1-15.

Bai X., Liang W., Sun J., Zhao C., Wang P., Zhang Y. (2022). Enhanced production of microalgae-originated photosensitizer by integrating photosynthetic electrons extraction and antibiotic induction towards photocatalytic degradation of antibiotic: A novel complementary treatment process for antibiotic removal from effluent of conventional biological wastewater treatment. Journal of Environmental Management, 308: 114527.

Ball C. (2009). Determination of penicillins in meat by high performance liquid chromatography (HPLC-UV) and HPLC-MS/MS. LCGC Europe, 22.

Bej S., Swain S., Bishoyi A.K., Mandhata C.P., Sahoo C.R., Padhy R.N. (2024). Recent advancements on antibiotic bioremediation in wastewaters with a focus on algae: an overview. Environmental Technology, 45(21): 4214-4229.

Chen Y., Jiang C., Wang Y., Song R., Tan Y., Yang Y.,

Zhang Z. (2022). Sources, environmental fate, and ecological risks of antibiotics in sediments of Asia's longest river: a whole-basin investigation. Environmental Science and Technology, 56(20): 14439-14451.

Cheng X., Delanka-Pedige H.M., Munasinghe-Arachchige S.P., Abeysiriwardana-Arachchige I.S., Smith G.B., Nirmalakhandan N., Zhang Y. (2020). Removal of antibiotic resistance genes in an algal-based wastewater treatment system employing *Galdieria sulphuraria*: a comparative study. Science of the Total Environment, 711: 134435.

Chojnacka K., Skrzypczak D., Izydorczyk G., Mikula K., Szopa D., Moustakas K., Witek-Krowiak A. (2022). Biodegradation of pharmaceuticals in photobioreactors – a systematic literature review. Bioengineered, 13(2): 4537-4556.

Czyrski A. (2018). The HPLC method for fast determination of levofloxacin in liquid pharmaceutical formulations. Journal of Contemporary Pharmacy, 11; 67-71.

Duarte D.J., Zillien C., Kox M., Oldenkamp R., van der Zaan B., Roex E., Ragas A.M. (2023). Characterization of urban sources of antibiotics and antibiotic-resistance genes in a Dutch sewer catchment. Science of the Total Environment, 905: 167439.

Frascaroli G., Roberts J., Hunter C., Escudero A. (2024). Removal efficiencies of seven frequently detected antibiotics and related physiological responses in three microalgae species. Environmental Science and Pollution Research, 31(9): 14178-14190.

Hakim M.A.A., Al-Ghouti M.A., Das P., Abu-Dieyeh M., Ahmed T.A., Aljabri H.M.S. (2018). Potential application of microalgae in produced water treatment. Desalination and Water Treatment, 135: 47-58.

Hayes A., Murray L.M., Stanton I.C., Zhang L., Snape J., Gaze W.H., Murray A.K. (2022). Predicting selection for antimicrobial resistance in UK wastewater and aquatic environments: Ciprofloxacin poses a significant risk. Environment International, 169: 107488.

Hiibel S.R., Lemos M.S., Kelly B.P., Cushman J.C. (2015). Evaluation of diverse microalgal species as potential biofuel feedstocks grown using municipal wastewater. Frontiers in Energy Research, 3: 20.

Hom-Diaz A., Jaén-Gil A., Rodríguez-Mozaz S., Barceló D., Vicent T., Blánquez P. (2022). Insights into removal of antibiotics by selected microalgae. Algal Research, 61: 102560.

Hom-Diaz A., Norvill Z.N., Blánquez P., Vicent T., Guieysse B. (2017). Ciprofloxacin removal during secondary domestic wastewater treatment in high rate algal ponds. Chemosphere, 180: 33-41.

Huang F., Chen L., Zhang C., Liu F., Li H. (2022). Prioritization of antibiotic contaminants in China based on decennial national screening data and their persistence, bioaccumulation and toxicity. Science of the Total Environment, 806: 150636.

Jurado A., Pujades E., Walther M., Diaz-Cruz M.S. (2022). Occurrence, fate, and risk of the organic pollutants of the surface water watch list in European groundwaters: A review. Environmental Chemistry Letters, 20(5): 3313-3333.

Kumar N., Shukla P. (2023). Microalgal-based bioremediation of emerging contaminants: Mechanisms and challenges. Environmental Pollution, 337: 122591.

Li S., Hofstra N., van de Schans M.G., Yang J., Li Y., Zhang Q., ... Zhang F. (2023). Riverine antibiotics from animal production and wastewater. Environmental Science and Ecotechnology, 10(11): 1059-1067.

Li S., Liu Y., Wu Y., Hu J., Zhang Y., Sun Q., Ni J. (2022). Antibiotics in global rivers. National Science Open, 1(2): 20220029.

Li S., Show P.L., Ngo H.H., Ho S.H. (2022). Algae-mediated antibiotic wastewater treatment: A critical review. Environmental Science and Ecotechnology, 9: 100145.

Lu W., Xu C., Liu F., Su M., Cheng S., Zhang Y. (2023). Antibiotic removal efficiency by microalgae: A systematic analysis combined with meta-analysis. Process Safety and Environmental Protection, 174: 912-920.

Mnasser F., Martínez-Cartas M.L., Sánchez S. (2025). Production of bioproducts from wastewater treatment using the microalga *Neochloris oleoabundans*. Engineering in Life Sciences, 25(7): e70032.

Nguyen L.M., Nguyen N.T.T., Nguyen T.T.T., Nguyen T.T., Nguyen D.T.C., Tran T.V. (2022). Occurrence, toxicity and adsorptive removal of the chloramphenicol antibiotic in water: a review. Environmental Chemistry Letters, 20(3): 1929-1963.

Norvill Z.N., Toledo-Cervantes A., Blanco S., Shilton A., Guieysse B., Muñoz R. (2017). Photodegradation and sorption govern tetracycline removal during wastewater treatment in algal ponds. Bioresource Technology, 232: 35-43.

Pauletto M., De Liguoro M. (2024). A review on

fluoroquinolones' toxicity to freshwater organisms and a risk assessment. Journal of Xenobiotics, 14(2): 717-752.

Polianciuc S.I., Gurzău A.E., Kiss B., Ştefan M.G., Loghin F. (2020). Antibiotics in the environment: causes and consequences. Medicine and Pharmacy Reports, 93(3): 231.

Roy B., Suresh P.K. (2021). Toxic effect of antibiotics on freshwater algal systems and the mechanisms of toxicity: A review. Nature Environment and Pollution Technology, 20(4): 1611-1619.

Scherer R., Pereira J., Firme J., Lemos M., Lemos M. (2014). Determination of ciprofloxacin in pharmaceutical formulations using HPLC method with UV detection. Indian J. Pharm. Sci., 76(6); 541.

Valev D., Silva Santos H., Tyystjärvi E. (2020). Stable wastewater treatment with *Neochloris oleoabundans* in a tubular photobioreactor. Journal of Applied Phycology, 32(1): 399-410.

Vulsteke E., Van Den Hende S., Bourez L., Capoen H., Rousseau D.P., Albrecht J. (2017). Economic feasibility of microalgal-bacterial floc production for wastewater treatment and biomass valorization. Bioresource Technology, 224: 118-129.

Wang Y., Zhao R., Liu L., Li B., Zhang T. (2021). Selective enrichment of comammox from activated sludge using antibiotics. Water Research, 197: 117087.

Xiong Q., Hu L.X., Liu Y.S., Zhao J.L., He L.Y., Ying G.G. (2021). Microalgae-based technology for antibiotics removal: from mechanisms to application of innovational hybrid systems. Environment International, 155: 106594.

Yang Q., Gao Y., Ke J., Show P.L., Ge Y., Liu Y., ... Chen J. (2021). Antibiotics: An overview on the environmental occurrence, toxicity, degradation, and removal methods. Bioengineered, 12(1): 7376-7416.

Zhang D., Peng Y., Chan C.L., On H., Wai H.K.F., Shekhawat S.S., ... Tun H.M. (2021). Metagenomic survey reveals more diverse and abundant antibiotic resistance genes in municipal wastewater than hospital wastewater. Frontiers in Microbiology, 12: 712843.

Zhu L., Yuan L., Shuai X.Y., Lin Z.J., Sun Y.J., Zhou Z.C., ... Chen H. (2023). Deciphering basic and key traits of antibiotic resistome in influent and effluent of hospital wastewater treatment systems. Water Research, 231: 119614.