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Silicon as a potential bioremediation agent for mitigating aluminum toxicity in aquatic microalgae: Implications for sustainable agricultural ecosystems

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Silicon as a potential bioremediation agent for mitigating aluminum toxicity in aquatic microalgae: Implications for sustainable agricultural ecosystems

Abstract: Heavy metal pollution in agricultural and aquatic ecosystems seriously affect microorganisms essential for ecological balance. Microalgae, as primary producers, are particularly vulnerable to such contaminants while being vital components of sustainable agricultural systems. In this study, we conducted a controlled laboratory experiment to evaluate and compare the specific impacts of silicon (Si) and aluminium (Al) exposure on the growth, biomass, chlorophyll content, and morphology of three economically important microalgae species: *Chlorella vulgaris, Haematococcus pluvialis,* and *Tetraselmis suecica*. Cultures were exposed to varying concentrations of aluminium (1, 10, and 100 mg l^{-1}) and silicon (100, 150, and 200 mg l^{-1}) for three weeks under controlled conditions. Results demonstrated that aluminium caused a significant, concentration-dependent inhibition of growth (37–62 %), reduced total chlorophyll content, and induced morphological alterations such as cell swelling and chlorophyll degradation. Conversely, silicon treatment not only showed minimal adverse effects but also exhibited a partial protective role by maintaining higher growth and chlorophyll levels compared to Al-exposed groups. These findings clearly indicate that silicon can mitigate aluminium toxicity in microalgae, enhancing their resilience under metal stress. While not directly applicable to higher plants, these findings offer insight into microbial metalloid interactions relevant to Si-mediated crop protection.

Key words: silicon, aluminium toxicity, microalgae physiology, aquatic ecosystems, agricultural water quality.

Silicij kot potencialno bioremediacijsko sredstvo za ublažitev toksičnosti aluminija v vodnih mikroalgah: Posledice za trajnostne kmetijske ekosisteme

Izvleček: Onesnaženje s težkimi kovinami v kmetijskih in vodnih ekosistemih močno ogroža mikroorganizme, ki so bistveni za ekološko ravnovesje. Mikroalge kot primarni proizvajalci so še posebej občutljive na takšne onesnaževalce, medtem ko so bistvene sestavine trajnostnih kmetijskih sistemov. V tej raziskavi so izvedli nadzorovan laboratorijski poskus, da bi ocenili in primerjali posebne vplive izpostavljenosti siliciju (Si) in aluminiju (Al) na rast, biomaso, vsebnost klorofila in morfologijo treh gospodarsko pomembnih vrst mikroalg: *Chlorella vulgaris, Haematococcus pluvialis* in *Tetraselmis suecica.* Kulture so bile tri tedne v nadzorovanih razmerah izpostavljene različnim koncentracijam aluminija (1, 10 in 100 mg l^{-1}) in silicija (100, 150 in 200 mg l^{-1}). Rezultati so pokazali, da je aluminij povzročil pomembno, od koncentracije odvisno zaviranje rasti (37–62 %), zmanjšal skupno vsebnost klorofila in povzročil morfološke spremembe, kot sta nabrekanje celic in razgradnja klorofila. Nasprotno pa obravnavanje s silicijem ni pokazalo le minimalnih škodljivih učinkov, ampak tudi delno zaščitno vlogo z ohranjanjem večje rasti in večje vsebnosti klorofila v primerjavi s skupinami, izpostavljenimi Al. Te ugotovitve jasno kažejo, da lahko silicij ublaži toksičnost aluminija v mikroalgah in poveča njihovo odpornost na obremenitev s kovinami. Čeprav te ugotovitve niso neposredno uporabne za višje rastline, ponujajo vpogled v interakcije mikrobnih metaloidov, ki so pomembne za zaščito pridelka, posredovano s Si.

Ključne besede: silicij, toksičnost aluminija, fiziologija mikroalg, vodni ekosistemi, kakovost kmetijske vode.

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1 INTRODUCTION

Microalgae are fundamental components of aquatic ecosystems and have gained significant attention for their diverse applications in sustainable agriculture, biofuel production, wastewater treatment, and pharmaceutical products (Grönlund et al., 2004). As primary producers in agricultural watersheds and irrigation systems, microalgae contribute to nutrient cycling and are bioindicators of environmental health. However, their growth and biochemical composition are increasingly threatened by environmental stressors, particularly in agricultural landscapes where runoff can introduce various contaminants into aquatic systems. Heavy metals and metalloids from agricultural inputs and industrial activities have emerged as significant threats to microalgal communities. Silicon (Si) and aluminium (Al) are ubiquitous elements in agricultural soils and water systems that can accumulate in aquatic environments, potentially influencing the physiology and productivity of microalgae, and thus impacting the ecological functions of agricultural water systems (Quiroz-Vazquez et al., 2008). Silicon, a beneficial element for many plants including agricultural crops, has been recognized for its positive effects on cell wall formation, mechanical stability, and overall growth enhancement in various microalgae (Martin-Jézéquel et al., 2000). This element also plays a crucial role in mitigating biotic and abiotic stresses in crop plants, suggesting potential similar protective functions in microalgae under conditions of metal stress. Conversely, aluminium, while naturally abundant in agricultural soils, can exert toxic effects on microorganisms due to its ability to interfere with cellular processes and enzyme activities (Trenfield et al., 2015). Aluminium toxicity is a significant constraint in acidic soils worldwide, affecting approximately 40 % of arable lands and causing substantial yield reductions in sensitive crops. Understanding Al toxicity mechanisms in microalgae may provide insights into related processes in higher plants and guide strategies for maintaining healthy microalgal populations in agricultural water systems. *Chlorella vulgaris* Beijerinck, *Haematococcus pluvialis* Flotow, and *Tetraselmis suecica* (Kylin) Butcher are three widely studied microalgal species with diverse ecological roles and agricultural applications, including as biofertilizers, soil conditioners, and components of integrated farming systems. While extensive research has examined the physiological responses of these microalgae to various stressors (Ciccia et al., 2023), the specific effects of Si supplementation and Al toxicity on their growth and chlorophyll content in agricultural water contexts have not been comprehensively explored. Chlorophyll content and growth are among the most characteristic indicators of heavy metal stress in photosynthetic organisms, with toxicity causing alterations in chloroplast and cell membrane structure (Stoeva et al., 2005). These parameters serve as valuable metrics for assessing the impact of contaminants on photosynthetic efficiency and biomass production, which ultimately influence ecosystem functionality and water quality in agricultural systems. Although the protective role of Si has been documented in higher plants, the current study focuses exclusively on microalgae. Thus, while the findings may suggest potential strategies for mitigating Al toxicity in crops, direct extrapolation to plants requires further investigation. This research aims to compare the impacts of Si supplementation and Al toxicity on the growth, biomass, chlorophyll content, and morphology of *C. vulgaris, H. pluvialis*, and *T. suecica* within the context of agricultural water systems. The findings are anticipated to contribute to the development of strategies for mitigating the adverse effects of metal contamination on microalgal communities in agricultural watersheds, thereby preserving their ecological functions while potentially offering insights into crop protection mechanisms against Al toxicity. Additionally, this research may inform sustainable water management practices in agriculture and forestry, where understanding metalloid interactions is crucial for maintaining ecosystem health, productivity, and water quality.

2 MATERIALS AND METHODS

2.1 MICROALGA STRAINS AND CULTURE

The three species of microalgae, *Chlorella vulgaris, Haematococcus pluvialis*, and *Tetraselmis suecica* obtained from the French Culture Collection of Algae (Termar) were cultivated in sterilized blue-green medium (BG-11) supplemented with vitamins (B1, and B12) as previously described (Bischoff, 1963). The algae cells were incubated in a phytotron room maintained at a temperature of 26 °C and a photoperiod of a 12 hour light/12 hour dark cycle. The microalgae were grown in 250 ml Erlenmeyer flasks containing 150 ml of the liquid BG-11 medium to reach an initial algal cell density of 1×10^6 cells ml^{-1} prior to the experiment (day 0).

2.2 TREATMENT

The three growing microalgae strains, *Chlorella vulgaris, Haematococcus pluvialis*, and *Tetraselmis suecica*, were separately exposed to increasing concentrations of aluminum chloride hexahydrate (Sigma-Aldrich, CAS #: 7784-13-6); 0, 1, 10, and 100 mg l^{-1}, and silicon (SiO_2,

Sigma-Aldrich, 99.9 %); 0, 100, 150, and 200 mg l^{-1}, for 7, 14, and 21 days. The selected testing concentrations were chosen based on a preliminary test study conducted on these algal cells using various concentrations.

2.3 DETERMINATION OF DRY BIOMASS AND TOTAL CHLOROPHYLL CONTENT

The dry biomass content in the three strains was determined according to a previously reported protocol (Zhu & Lee, 1997). In brief, 5 ml from each microalgae sample was washed with distilled water, filtered on Whatman glass microfiber filters (1825-055) that were previously dried and weighed, and then heated in the oven at 105 °C for 1 hour, then weighed again. The total chlorophyll content of each microalgae strain, treated separately with Al or Si, was determined at different time intervals (7, 14, and 21 days), as reported elsewhere (Porra et al., 1989)"type":"article-journal","volume":"975"},"uris":["http://www.mendeley.com/documents/?uuid=b5997d37-49d0-42b3-9463-2942431674bf","http://www.mendeley.com/documents/?uuid=d01d457e-5b1e-40ff-855c-1b3f863ec798","http://www.mendeley.com/documents/?uuid=6e3f721c-ea2d-4d4f-851a-947255397f96"]}],"mendeley":{"formattedCitation":"(Porra et al., 1989. Briefly, 0.05 g of freeze-dried microalgae was mixed with 8 ml of acetone solution (80% (v/v) and 2.5 mM sodium phosphate buffer, pH 7.8) for 16 hours. After that, samples were centrifuged at 2,000 × g for 2 minutes, the supernatant was removed, and the algal cell pellet was washed with 2 ml of acetone, centrifuged twice, and the acetone fractions were pooled. The final volume was adjusted to 15 ml with acetone. The chlorophyll absorbance was determined using a UV–Vis spectrophotometer (Thermo-Scientific, USA), and the total chlorophyll content was calculated using the following equation.

$$Total\ chlorophyll\ Content\ (\%\ w/w) = \frac{16.76\ x\ [A_{645}] + \ 734\ x\ [A_{663}]}{mass\ of\ sample}$$

2.4 DETERMINATION OF CELL GROWTH INHIBITION

Cell growth inhibition of control cells and those treated with aluminum and silicon was determined based on the calculation of the rate of cell growth. The inhibition percentage (I %) at each concentration of each chemical was calculated as follows:

$$I\% = \frac{\mu_c - \mu}{\mu_c} x\ 100$$

Where μ is the mean value for the average specific growth rate in control test algal cells and μ is the average specific growth rate for the treatment replicates.

2.5 MORPHOLOGICAL EVALUATION

Morphological changes in the tested microalgae were examined using a light microscope (Carl Zeiss, Germany) at 40 × magnification, equipped with a digital camera (AxioCam ICc 3) connected to a computer. Image capture and size analysis were performed using AxioVision software (version 4.8.2.0, Carl Zeiss). Representative micrographs were obtained from three independent cultures, with a scale bar of 20 μm included in the figures.

2.6 STATISTICAL ANALYSIS

All experiments were performed at least three times, and data are expressed as mean ± SD. Statistical analysis was carried out using one-way ANOVA followed by Tukey's post hoc test (GraphPad Prism Software) to compare treatment groups with the control. Differences were considered statistically significant at $p \leq 0.05$, denoted as $^{*}p < 0.05$, $^{**}p<0.01$, and $^{***}p < 0.001$ versus control

3 RESULTS AND DISCUSSION

3.1 DRY BIOMASS AND TOTAL CHLOROPHYLL CONTENT

As shown in Figure 1, aluminium and silicon treatments significantly increased biomass in all three algal species in a concentration- and time-dependent manner, while silicon treatment produced smaller but statistically significant increases in several comparisons versus control. In *Chlorella vulgaris*, biomass was increased markedly by all Al concentrations (p <0.01 at day 7; $p < 0.001$ at day 14 and 21). Si treatments caused less pronounced but significant increases at some time points (typically $p < 0.05$). In *Haematococcus* ., Al 100 mg l^{-1} increased biomass from day 7 onward ($p < 0.01$ at days 7 and 14; $p < 0.001$ at day 21), and Al 1 and 10 mg l^{-1} produced modest increases ($p < 0.05$ at days 7; $p < 0.01$ at day 14; and $p < 0.001$ at day 21). Si treatments produced small but significant increases in a subset of comparisons ($^{*}p < 0.05$). In *Tetraselmis* ., all Al treatments increased biomass ($p < 0.01$ at all time points), and Si treatments again

yielded milder yet significant increases ($p < 0.05$). Collectively, Al treatment, particularly at 100 mg l^{-1} produced the largest increases in biomass across species, while Si treatment produced modest but statistically significant increases in several instances. The observed biomass increase under Al stress may reflect hormesis, where low levels of stressors stimulate compensatory biological responses that enhance growth (Kaur et al., 2024; Zhou et al., 2024). Similar hormetic responses have been reported in *Chromochloris zofingiensis* (Dönz) Fucíková & L.A.Lewis exposed to cadmium, where sub-lethal stress enhanced biomass production (Y. Zhang et al., 2024). Moreover, recent studies show that hormetic responses are not limited to heavy metals, as nanomaterial-induced stress can also increase microalgal biomass and photosynthetic efficiency under specific conditions (Hidalgo et al., 2023). Silicon supplementation further supports growth by mitigating oxidative stress and modulating antioxidant enzyme activities, consistent with its role in higher plants, where it stabilizes cell walls, alleviates metal toxicity, and enhances stress resilience (Denarié et al., 2025; Ma & Naoki Yamaji, 2015; Saleem et al., 2025; Wanas et al., 2025). Previous studies mainly focused on Al toxicity without evaluating protective agents like Si. Our findings indicate that microalgae can exhibit both adaptive and hormetic responses to metal stress, and Si supplementation may enhance biomass production and stress tolerance, offering potential for biotechnological applications (Cavalletti et al., 2025; Ding, 2025).

In Figure 2, aluminium treatment generally decreased total chlorophyll content in all three algal species, whereas silicon treatment had little to no significant effect compared with the control. In *Chlorella v.*, Al treatments significantly reduced chlorophyll levels for all Al concentrations vs. control ($p < 0.01$ at day 7, $p < 0.001$ at days 14 and 21), while Si treatments showed no significant difference (ns). In *Haematococcus p.*, Al treatments decreased chlorophyll all Al concentrations and treatment exposure time vs. control ($^{**}p < 0.01$), with no effect observed for Si (ns). In *Tetraselmis s.*, the same overall pattern was observed: Al decreased chlorophyll content significantly at day 7 ($^{**}p < 0.01$), days 14 and 21 ($p < 0.001$), while Si

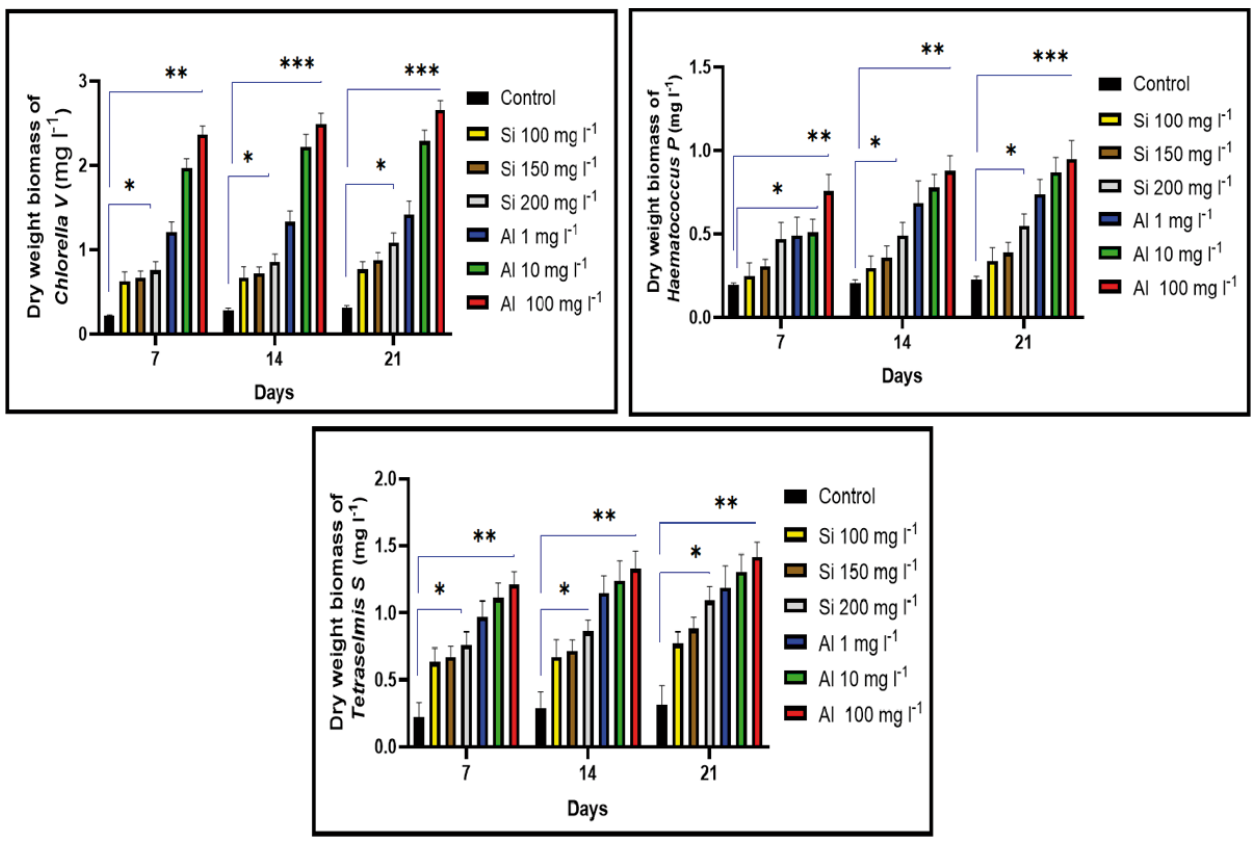

Figure 1: Dry biomass of *Chlorella vulgaris*, *Haematococcus pluvialis*, and *Tetraselmis suecica* exposed to aluminium (Al; 1, 10, and 100 mg l-*1*) and silicon (Si; 100, 150, and 200 mg l-*1*) for 7, 14, and 21 days. Values are presented as mean ± SD (n = 3 independent cultures per species). Different letters above bars indicate statistically significant differences between treatments at each time point ($p < 0.05$).

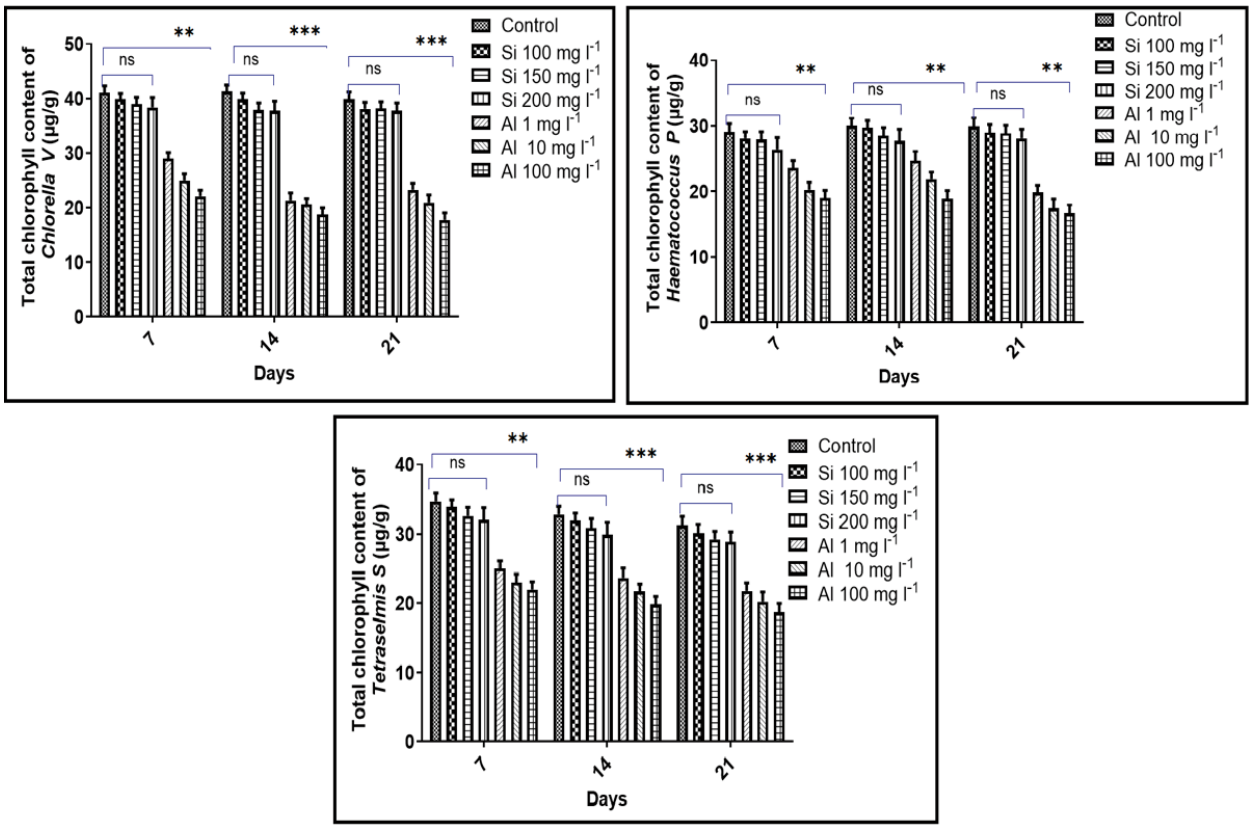

Figure 2: Total chlorophyll content in *Chlorella vulgaris*, *Haematococcus pluvialis*, and *Tetraselmis suecica* exposed to aluminium (Al; 1, 10, and 100 mg l^{-1}) and silicon (Si; 100, 150, and 200 mg l^{-1}) for 7, 14, and 21 days. Values are mean ± SD (n = 3 independent cultures per species). Different letters indicate statistically significant differences compared with the control ($p < 0.05$).

treatments showed no significant differences from the control at any time point. Collectively, these findings indicate that Al treatment consistently and significantly decreased total chlorophyll content in all three algal species, with the strongest reductions observed at higher concentrations and later time points, whereas Si treatment produced no measurable effects. It is important to note that microalgae and higher plants differ considerably in physiology and uptake pathways, so direct extrapolation to cultivated plants should be done with caution. Aluminium is known to induce oxidative toxicity in some microalgae species (Jeffrey & Haxo, 1968), whereas silicon can be beneficial even at higher concentrations (Hou et al., 2023; Zhang et al., 2023). Consistently, this study revealed a marked increase in dry biomass under Al stress, aligning with recent findings (Kaur et al., 2024; Yang et al., 2023). The observed chlorophyll reduction under Al stress is consistent with reports that heavy metals inhibit chlorophyll biosynthesis and promote degradation via oxidative stress (Rao et al., 2025; Sharma et al., 2025). Conversely, Si supplementation alleviates metal-induced chlorophyll loss by enhancing antioxidant defenses and stabilizing chloroplast membranes, thereby preserving photosynthetic capacity (Manimaranet al., 2015; Monteiro, 2022). These protective effects help maintain photosynthetic efficiency and support growth under stress conditions.

3.2 CELL GROWTH INHIBITION

Figure 3 illustrates that aluminium (Al) exposure significantly inhibited algal growth in a concentration- and time-dependent manner. After 7 days of exposure, Al concentrations of 1, 10, and 100 mg l^{-1} resulted in growth inhibition of 37 %, 46 %, and 59 % in *Chlorella vulgaris* and *Haematococcus pluvialis*, respectively. In contrast, *Tetraselmis suecica* exhibited higher sensitivity, with growth inhibitions of 49 %, 55 %, and 62 % under the same Al concentrations. These findings are consistent with previous reports showing concentration-dependent inhibition of *Chlorella* and *Scenedesmus* growth by Al_2O_3 nanoparticles (72-h EC_{50} ≈ 45 mg l^{-1} and 39 mg l^{-1}, respectively) (Sadiq et al., 2011), as well as long-term in-

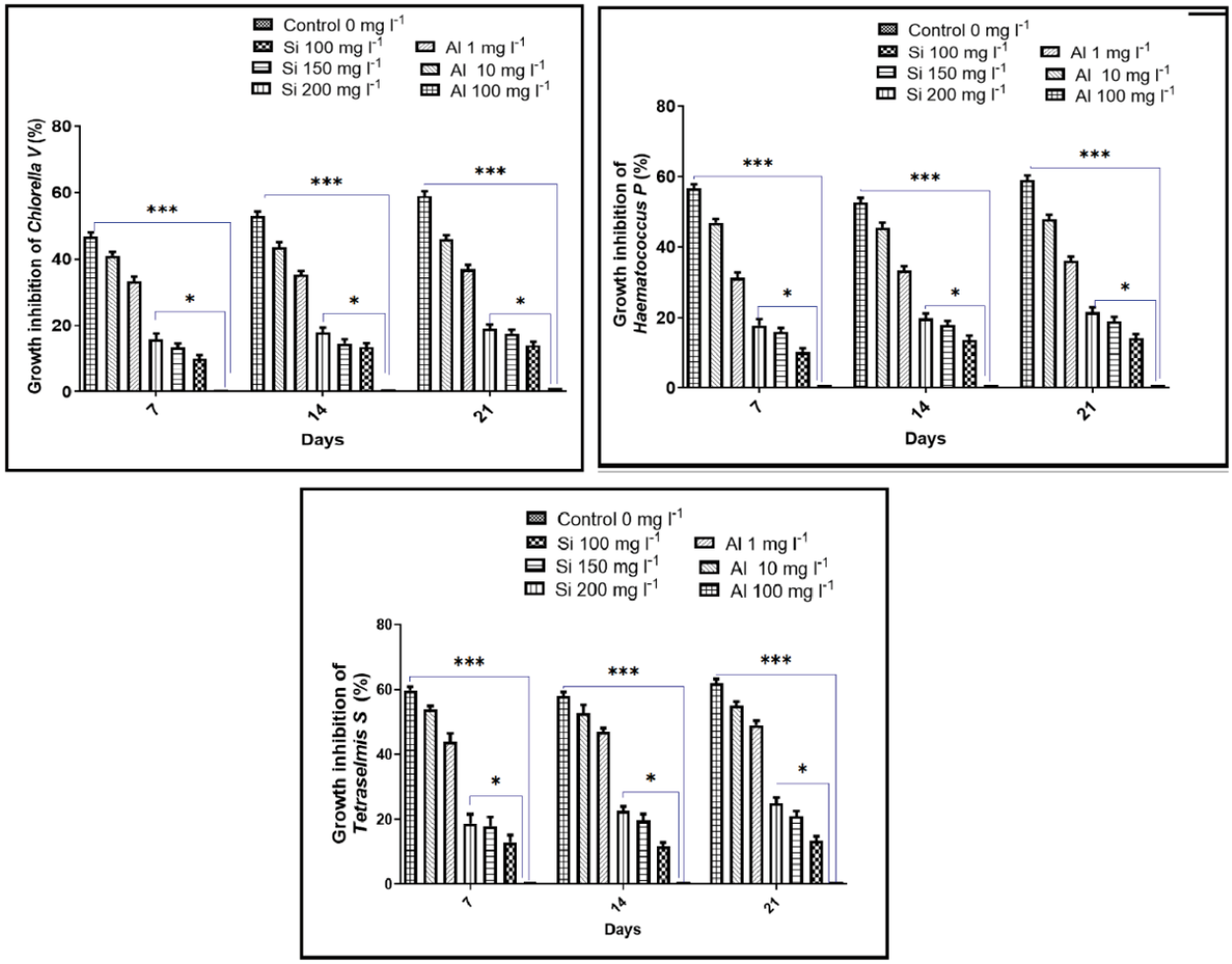

Figure 3: Growth inhibition (%) in *Chlorella vulgaris*, *Haematococcus pluvialis*, and *Tetraselmis suecica* exposed to aluminium (Al; 1, 10, and 100 mg l^{-1}) and silicon (Si; 100, 150, and 200) for 7, 14, and 21 days. Values are mean ± SD (n = 3 independent cultures per species). Different letters indicate statistically significant differences compared with the control ($p < 0.05$).

hibition (20–40 %) of *Scenedesmus armatus* (Chodat) Chodat growth under Al nanoparticle exposure(Cortés-Téllez et al., 2024). Similar reductions in chlorophyll content and photosynthetic performance were also documented in *Dunaliella salina* (Dunal) Teodoresco exposed to Al_2O_3 nanoparticles (Shirazi et al., 2015). These findings suggest that *C. vulgaris* is the most susceptible species to Al-induced growth inhibition among the tested microalgae. Conversely, silicon (Si) treatment led to only modest and statistically insignificant growth reductions (~15 %, 19 %, and 23 % across the three strains) after 7 days. Notably, this inhibitory effect diminished with prolonged exposure periods, indicating a potential acclimation or reduced bioavailability of Si over time. However, the efficacy of Si in mitigating Al-induced toxicity in microalgae does not necessarily extrapolate to crop plants. Further experimental validation under field-relevant agricultural conditions is imperative. Importantly, comparable Si-mediated alleviation of Al toxicity has been reported in higher plants, including upland rice (where Si reduced Al translocation to shoots) (Munyaneza et al., 2024), *Eucalyptus platyphylla F.Muell.* (Si decreased ROS accumulation and improved pigments and gas exchange) (Lima et al., 2016), Tartary buckwheat (enhanced antioxidant defenses) (Qi et al., 2024), and maize exposed to SiO_2 nanoparticles (increased detoxification and antioxidative activity) (De Sousa et al., 2019). These studies support the hypothesis that Si supplementation confers cross-kingdom protection against Al toxicity. The inhibitory effects of Al and Al-based nanoparticles (nanoAl) on algal growth have been extensively documented (Das et al., 2023; Gebara et al., 2023; Nurhidayati et al., 2023), further corroborating the detrimental impacts on algal biomass and photosynthetic efficiency. In con-

trast, Si and Si-based nanoparticles have been reported to exhibit minimal toxicity to algal cells. For instance, a negligible growth inhibition was reported in *Chlorella vulgaris* upon exposure to SiO_2 nanoparticles (Ahmed et al., 2023; Maia et al., 2024; Yadav et al., 2023). Similarly, no adverse effect on algal growth was reported in Si treatments, suggesting a potential role for Si in alleviating metal-induced stress in microalgae (Ghariani et al., 2025; Manimaran et al., 2015). Molecular and biochemical analyses have elucidated the mechanisms underlying Al-induced growth inhibition in microalgae. Alterations in photosynthetic pigment content, reactive oxygen species (ROS) accumulation, and enzyme activity were reported as key responses to Al stress (Tejada-Alvarado et al., 2023; Verma et al., 2023; Yadav et al., 2023). Also, Al exposure disrupts cellular homeostasis, leading to oxidative damage and impaired metabolic functions (Yadav et al., 2023). These findings are in line with earlier mechanistic studies showing lipid peroxidation, cell aggregation, and antioxidant suppression in *Scenedesmus* under Al stress(Hamed et al., 2019).

3.3 MORPHOLOGICAL CHANGES

Light microscopy analysis revealed that the three tested microalgal species exhibited normal morphology under control conditions, characterized by uniform cell size, intact cell walls, and well-defined chlorophyll pigmentation (Figures 4A, 5A, and 6A). In contrast, exposure to aluminium (Al) induced concentration-dependent morphological alterations, including abnormal cell enlargement, cytoplasmic disorganization, and localized chlorophyll depletion (Figures 4E–F, 5E–F, and 6E–F). These effects are consistent with the disruption of photosynthetic structures and stress-induced vacuolation commonly reported under Al toxicity. Cells exposed to silicon (Si) treatment also exhibited minor morphological modifications, but these changes were significantly less pronounced compared to Al-treated groups, suggesting a potential protective effect of Si against structural damage. These findings align with previous reports demonstrating Al-induced structural changes in green microalgae, including cell wall thickening, chloroplast disintegration, and pigment degradation (Hamed et al., 2019). Comparable protective effects of Si supplementation have also been observed, where Si mitigated ultrastructural and pigment-level alterations in algae and higher plants under metal stress (De Sousa et al., 2019; Mock, 2021; Pakrashi et al., 2013; Přibyl et al., 2008; Qi et al., 2024)Taken together, the observed reductions in chlorophyll content, growth, and alterations in cellular morphology highlight the sensitivity of *C. vulgaris*, *H. pluvialis*, and *T. suecica* to Al stress, as well as the mitigating role of Si supplementation. Also, the findings of this study carry important practical implications for agricultural water systems, particularly irrigation practices in areas affected by aluminium contamination. By demonstrating that silicon supplementation mitigates Al-induced growth inhibition and chlorophyll degradation in *C. vulgaris*, *H. pluvialis*, and *T. suecica*, our results suggest that Si can play a protective role in maintaining the structural and functional integrity of microalgal communities.

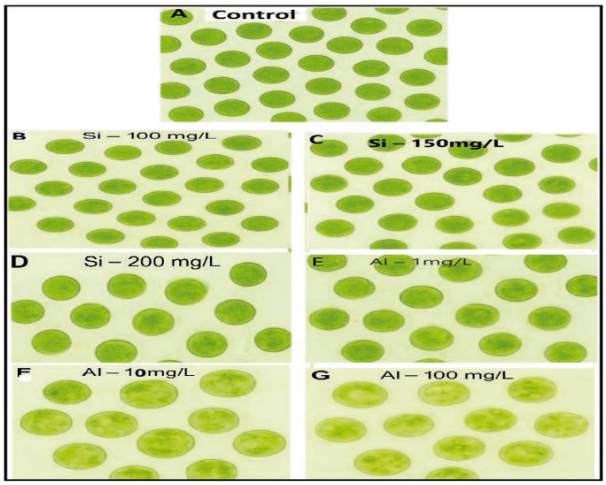

Figure 4: Light micrographs (40×) of *Chlorella vulgaris* after 21 days of exposure. (A) Control cells showing normal morphology with uniform size, intact cell walls, and distinct chlorophyll pigmentation. (B–D) Cells exposed to silicon (Si) at 100, 150, and 200 mg l^{-1}, respectively, exhibiting largely preserved morphology with only minor structural modifications and negligible pigment loss compared to control. (E–G) Cells exposed to aluminium (Al) at 1, 10, and 100 mg l^{-1}, respectively, displaying concentration-dependent alterations, including cell enlargement, cytoplasmic disorganization, vacuolation, and localized chlorophyll depletion. Representative images are shown from *n* = 3 independent cultures. Scale bar = 20 µm.

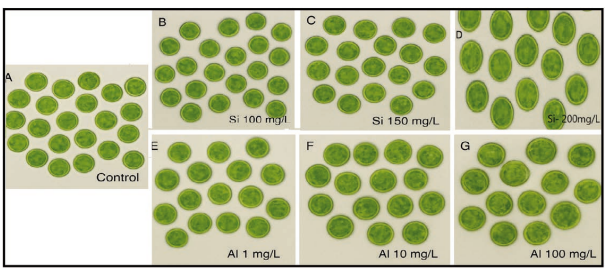

Figure 5: Light micrographs (40×) of *Haematococcus pluvialis* after 21 days of exposure. (A) Control cells showing normal spherical morphology with intact cell walls and well-defined chlorophyll pigmentation. (B–D) Cells exposed to silicon (Si) at 100, 150, and 200 mg l^{-1}, respectively, exhibiting largely preserved cellular structure with only slight changes in pigmentation and minimal morphological alterations compared to control. (E–G) Cells exposed to aluminium (Al) at 1, 10, and 100 mg l^{-1}, respectively, displaying concentration-dependent abnormalities, including cell enlargement, deformation of cell shape, partial chlorophyll depletion, and cytoplasmic disorganization. Representative images are shown from *n* = 3 independent cultures. Scale bar = 20 µm.

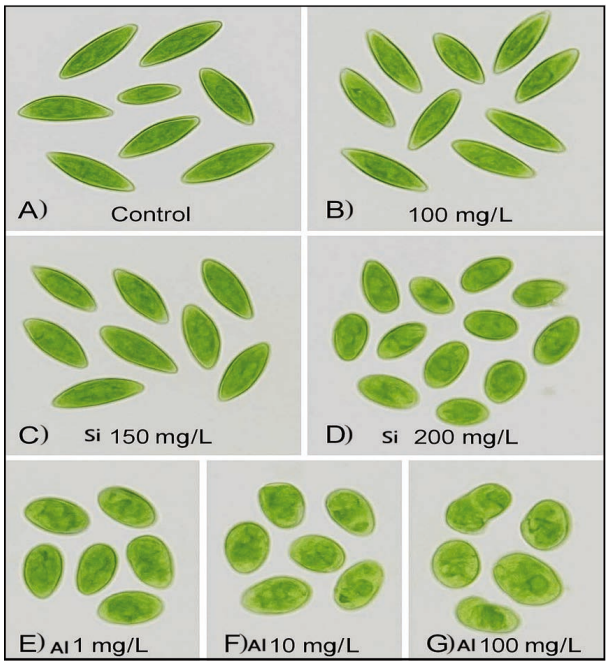

Figure 6: Light micrographs (40×) of *Tetraselmis suecica* after 21 days of exposure. (A) Control cells showing normal morphology with characteristic elongated shape, intact cell walls, and uniform chlorophyll pigmentation. (B–D) Cells exposed to silicon (Si) at 100, 150, and 200 mg l^{-1}, respectively, retained overall structural integrity, with only minor pigment variation and limited morphological alterations compared to control. (E–G) Cells exposed to aluminium (Al) at 1, 10, and 100 mg l^{-1}, respectively, exhibited concentration-dependent structural damage, including cell enlargement, deformation of the elongated cell shape, chlorophyll depletion, and cytoplasmic disorganization. Representative images are shown from $n = 3$ independent cultures. Scale bar = 20 µm.

Since microalgae are essential contributors to nutrient cycling, oxygen production, and the stability of aquatic ecosystems, safeguarding their viability is crucial for sustaining water quality in agricultural watersheds. These insights can be incorporated into strategies for mitigating the adverse effects of metal contamination by introducing Si amendments into irrigation systems or agricultural runoff management. Controlled Si supplementation could reduce the bioavailability and toxicity of Al, thereby enhancing the resilience of aquatic microflora while simultaneously lowering potential risks to crops irrigated with contaminated water. Such approaches could form part of integrated water management frameworks that aim to balance agricultural productivity with ecological protection. In a broader context, our results contribute to sustainable water management practices in agriculture and forestry. Understanding the interactions between Si and Al provides valuable guidance for designing bioremediation strategies that reduce metal stress in aquatic environments, preserve biodiversity, and improve ecosystem services. The incorporation of Si into water management not only supports the health of microalgal communities but also offers indirect benefits for crop protection, soil quality, and long-term sustainability of agroecosystems. Thus, the outcomes of this research provide both mechanistic insights and practical directions for addressing the challenges posed by metal contamination in managed ecosystems.

4 CONCLUSION

Our study demonstrates that aluminium treatment causes significant adverse effects on *Chlorella vulgaris*, *Haematococcus pluvialis*, and *Tetraselmis suecica*, including growth inhibition, decreased chlorophyll content, and morphological alterations. In contrast, silicon exposure exhibits minimal toxicity, suggesting its potential as a protective agent against aluminium stress in aquatic ecosystems. These results highlight the importance of understanding Si–Al interactions in aquatic microorganisms, particularly in relation to water quality management and the stability of aquatic ecosystems connected to agriculture. While the findings are limited to controlled laboratory conditions on microalgae and cannot be directly extrapolated to higher plants, they provide useful insight into processes that may influence agricultural water systems. Future research should therefore not only explore the molecular mechanisms underlying silicon's protective effects in microalgae, but also evaluate whether such protective interactions occur in crops under field-relevant agricultural conditions.

Ethics statement: This research was conducted using microalgae cultures only and did not involve human participants or animal subjects. All procedures were performed under controlled laboratory conditions in compliance with institutional biosafety guidelines and the ethical standards of the field.

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Conflict of interest:The authors declare no competing interests.

Data Availability

All data supporting the findings of this study have been deposited in the Zenodo repository and are openly accessible. The dataset includes the original research data in Excel format. The dataset has also been cited in the reference list as: Issaad, G. (2025). Dataset of the physiological parameters, dry mass, chlorophyll content and growth inhibition of *Chlorella vulgaris*, *Haematococcus pluvialis*, and *Tetraselmis suecica* exposed to aluminum (Al; 1, 10, and 100 mg l^{-1}) and silicon (Si; 100, 150, and 200 mg l^{-1}) for 7, 14, and 21 days. [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17665018.

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