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Comparative Study on the Impact of Simulated Industrial Smokes Nutrient Uptake Dynamic in Wastewater Treatment

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Abstract
This study investigated the effects of different artificial smokes (coal, rice straw, and petroleum) on the growth, nutrient uptake, and carbon dioxide (CO_2) bio fixation of a dominant microalgal strain (Scenedesmus obliquus) isolated from Nile River water. The microalgae were cultured in secondary-treated wastewater under controlled conditions, with and without exposure to the simulated smoke. The results demonstrated that the isolated microalgal strain exhibited remarkable tolerance to all three types of smoke exposure. While all smoke types positively impacted algal growth and nutrient uptake, rice straw smoke was found to be the most beneficial, leading to the highest biomass production and nutrient removal efficiency. Coal smoke exposure also showed a positive effect, albeit to a lesser extent. Interestingly, petroleum smoke exposure had a minimal impact on algal growth and nutrient uptake, suggesting that the microalgal strain may possess inherent tolerance to petroleum-derived pollutants. These findings highlight the potential of microalgae as a sustainable and efficient technology for wastewater treatment and CO2 mitigation, even in environments contaminated with industrial emissions.
Keywords: Microalgae; Industrial Smokes; CO2 biofixation; Wastewater treatment

1. Introduction

The challenge of achieving sustainable societal development is increasingly recognized as a global imperative. One of the primary contributors to climate change is the anthropogenic emission of carbon dioxide (CO_2) from industrial activities, which has been identified as a significant factor in global warming [1]. Data from the Global Carbon Project indicates that global CO_2 emissions from fossil fuel combustion reached 36.4 gigatons (Gt) in 2021, significantly surpassing the Earth's natural carbon sequestration capabilities of approximately 21 Gt per year. The rebound in emissions in 2020, following the economic recovery from the COVID-19 pandemic, further underscores the urgent need for effective strategies to mitigate greenhouse gas emissions [2].

In response to the pressing threat of climate change, countries around the world have committed to international agreements such as the Paris Agreement, which aims for climate neutrality by mid-century. At COP27 in Egypt, it was agreed that significant investments would be required to transition to a low-carbon global economy. More than 190 parties have ratified the Paris Agreement, with over 120 countries setting ambitious targets for achieving net-zero emissions [3]. These commitments highlight the global recognition of the need for collaborative efforts to tackle climate change and its associated impacts.

Among the various strategies for carbon mitigation, the utilization of microalgae has emerged as a promising avenue. Microalgae, some of the oldest photosynthetic organisms on Earth, possess a remarkable ability to capture and utilize CO_2. They can achieve growth rates and carbon fixation efficiencies that far exceed those of terrestrial plants, making them valuable for carbon sequestration [4]. The capacity of microalgae to assimilate a variety of inorganic carbon sources—including CO_2, carbonates, and bicarbonates—further enhances their potential in carbon capture applications [5].

The carbon content in microalgal biomass typically exceeds 50% of its dry weight, with estimates suggesting that approximately 1.83 tons of CO_2 can be fixed to produce one ton of microalgal biomass. This high carbon uptake, combined with their ability to utilize nitrogen and other nutrients, positions microalgae as effective agents

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for mitigating carbon and nutrient pollution in wastewater [6]. Recent research has increasingly focused on utilizing industrial waste, such as wastewater and flue gases, to cultivate microalgae, which not only addresses pollution but also reduces cultivation costs [7].

Despite their potential, the development of microalgae-based carbon fixation technologies is still in its infancy. A comprehensive assessment of the economic and environmental sustainability of microalgae cultivation remains necessary. Significant advancements in research and development, market evaluation, and policy frameworks are essential to fully leverage the benefits of microalgae in carbon capture and nutrient recovery [4].

Industrial sectors are significant contributors to global CO_2 emissions, particularly those reliant on energy-intensive manufacturing processes. While many economies are transitioning to low-carbon solutions in electricity, heat, and transport, decarbonizing heavy industries remains a complex challenge due to their close ties to economic growth and employment [8]. Over 100 countries still depend heavily on fossil fuels within their industrial supply chains, necessitating innovative approaches such as Carbon Capture Utilization and Storage (CCUS) to facilitate both economic development and decarbonization [8].

The search for alternative resources and sustainable processes for producing renewable chemicals and fuels continues to gain momentum, particularly in the context of mitigating climate risks associated with greenhouse gas emissions [9]. Microalgae, with their rapid growth rates and adaptability, offer a viable solution for nutrient recovery and biofuel production. They efficiently utilize nutrients from waste streams, converting them into valuable biomass [10]. Since the 1950s, microalgal biomass has been recognized as a potential feedstock for biofuels, primarily due to its high lipid content [11]. However, the economic viability of single-product value chains has been questioned, leading to an exploration of co-production strategies that yield both fuels and higher-value biochemicals [12].

The diverse potential of microalgae extends beyond biofuels to include nutraceuticals, pharmaceuticals, and bioplastics, reflecting the principles of a third-generation biorefinery [13]. For instance, the protein content of microalgal species such as *Arthrospira* (*Spirulina*) can reach up to 70% on a dry weight basis, making it a popular dietary supplement [14]. Additionally, microalgae can produce various bioactive compounds and polysaccharides that find applications in cosmetics and pharmaceuticals [15].

The environmental benefits of utilizing microalgae in wastewater treatment are manifold. Microalgae not only capture CO_2 but also assimilate nutrients such as nitrogen and phosphorus from wastewater, thus addressing eutrophication—a significant environmental concern in aquatic systems [16]. By employing microalgae in wastewater treatment, industries can reduce nutrient loads and improve effluent quality while simultaneously generating valuable biomass [17–21].

The dynamics of nutrient uptake in microalgae are influenced by various factors, including light availability, CO_2 concentration, and the presence of pollutants, such as simulated industrial smoke. The impact of these factors on microalgal growth and nutrient utilization is critical for optimizing wastewater treatment processes. Understanding how industrial emissions affect microalgal physiology can inform the development of more effective treatment strategies that leverage the natural capabilities of these organisms.

This study aims to investigate the effects of simulated industrial smoke on the nutrient uptake dynamics of microalgae during wastewater treatment processes. By examining the interactions between industrial emissions and microalgal growth, this research seeks to contribute to the understanding of how to maximize the efficacy of microalgae in treating wastewater while addressing CO_2 emissions. Ultimately, this study will provide insights into the feasibility of integrating microalgal systems into existing wastewater treatment frameworks, thereby promoting sustainable industrial practices.

In conclusion, the urgent need to address climate change and reduce greenhouse gas emissions calls for innovative solutions that integrate economic development with environmental sustainability. Microalgae present a promising option for carbon capture and nutrient recovery, particularly in the context of wastewater treatment. By exploring the impacts of simulated industrial smoke on nutrient uptake dynamics in microalgae, this study aims to advance the understanding of how these organisms can be effectively utilized in real-world applications. As the global community strives toward achieving climate neutrality, the role of microalgae in environmental management and sustainable industrial practices will undoubtedly be pivotal.

2. Material and methods

This study employed a rigorous experimental design to investigate the impact of simulated industrial smoke on microalgal growth and CO_2 biofixation. A lab-scale burner system was installed to generate controlled smoke emissions, primarily composed of carbon dioxide (CO_2).

2.1. Burner System Construction and Setup

Lab scale scale-designed burner system was constructed, consisting of a burner chamber, smoke transfer tubes, and a smoke collection bottle. This system enabled the continuous combustion of various materials, including coal, petroleum, and rice straw materials, to simulate industrial smoke conditions. The generated smoke was then transferred to a microalgae batch culture unit, where it was exposed to a microalgal strain (*Scenedesmus obliquus*) isolated from the Nile River water culture. The isolated strain present in the samples was identified using [22].

2.2. Species Isolation

The dominant algal species, *Scenedesmus obliquus*, was isolated through a series of purification steps. A modified BG11 growth medium [23], was used to culture the isolated species Table (1)

Table 1 BG11 medium composition

Macroelement nutrient	**Concentration (mg·L^{-1})**
$NaNO_3$	500.00
K_2HPO_4	40.00
MgSO4·7H2O	75.00
CaCl2·7H2O	36.00
Citric acid	6.00
Na_2CO_2	20.00
Na_2EDTA	1.00
Ferric ammonium citrate	6.00
Microelement nutrient	**Concentration (g·L^{-1})**
H_3BO_3	2.860
$MnCl_2·4H_2O$	1.810
$ZnSO_4·7H_2O$	0.222
$Na_2MoO_4·2H_2O$	0.390
$CuSO_4·5H_2O$	0.079
$Co(NO_3)_2·6H_2O$	0.0494

2.3. Smoke Exposure

Raw wastewater was subjected to a 24-hour settling period followed by a 24-hour anaerobic treatment phase. Subsequently, the wastewater was inoculated with isolated microalgae and exposed to the simulated smoke. The experimental design involved a control group without smoke exposure and treatment groups exposed to different types of smoke, including coal, petroleum, and rice straw smoke. To evaluate the impact of smoke exposure, a comprehensive range of analytical procedures was implemented. These included:

Chlorophyll a concentration was measured to assess algal biomass, pH (was measured using a Jenway pH meter model 3505), and alkalinity was monitored to calculate dissolved CO_2 levels [24], Dissolved oxygen (DO) was measured in mg/L using a Thermo Scientific Orion Star DO meter, Nutrient concentrations, including nitrate, orthophosphate, ammonia, and nitrite, were determined using standard analytical methods [25,26].

2.4. Experimental Design

The isolated *Scenedesmus obliquus* strain was exposed to different types of simulated smoke, and its growth response, nutrient uptake, and CO_2 biofixation rates were monitored. The experimental design included a control group without smoke exposure and treatment groups exposed to coal, petroleum, and rice straw smoke.

By following this rigorous methodology, the study aimed to provide valuable insights into the potential of microalgae to mitigate the environmental impact of industrial emissions and contribute to sustainable waste management practices.

3. Results and discussions

3.1. The impact of the Coal smoke

The objective of the coal smoke test was to evaluate the impact of exposed coal smoke wastewater sample (ECWW) on algal growth, nutrient uptake, and CO_2 biofixation in a secondary treated wastewater sample inoculated with the most adapted isolated *Scenedesmus obliquus* strain, compared to an unexposed coal smoke wastewater sample (UCWW). The aim was to determine whether coal smoke exposure creates a favorable environment for algal growth.

3.1.1. Algal growth response in the inoculated wastewater under coal smoke exposure

In the first three days following inoculation into the wastewater (Figure 1), algal growth progressed slowly, consistent with the lag phase commonly observed in microbial cultures. A sharp rise in biomass accumulation occurred between days 4 and 11, marking the transition to exponential growth. This phase was followed by a brief stabilization period (3 days) before growth rates began to decline after day 14. Notably, chlorophyll-a concentrations peaked at 3345.7 µg/L in smoke-exposed cultures (ECWW) on day 11, slightly exceeding the maximum of 3100.81 µg/L observed in unexposed samples (UCWW). The growth trajectory of Scenedesmus obliquus underscores its capacity to thrive under smoke-exposed conditions. The sequential progression from lag to exponential growth mirrors established microbial growth curves, while the elevated biomass in ECWW cultures indicates possible metabolic adjustments to industrial emissions, potentially enhancing pollutant tolerance or nutrient uptake efficiency.

This finding corroborates with González-Camejo *et al.* (2021) [27], who reported similar growth enhancement in *Scenedesmus* species under controlled stress conditions. The smoke exposure may have provided additional carbon sources and trace elements beneficial for algal growth, as suggested by Zhao *et al.* (2015) [28] in their study of industrial flue gas utilization by microalgae.

During the course of the experiment, dissolved oxygen (DO) concentrations were regularly measured to track changes associated with algal development in wastewater samples. The findings demonstrated a clear relationship between the amount of dissolved oxygen and the proliferation of algae. Specifically, as the DO levels rose, the algae exhibited faster growth rates. The peak growth was observed when DO values reached approximately 9.8 mg/L in the ECWW samples.

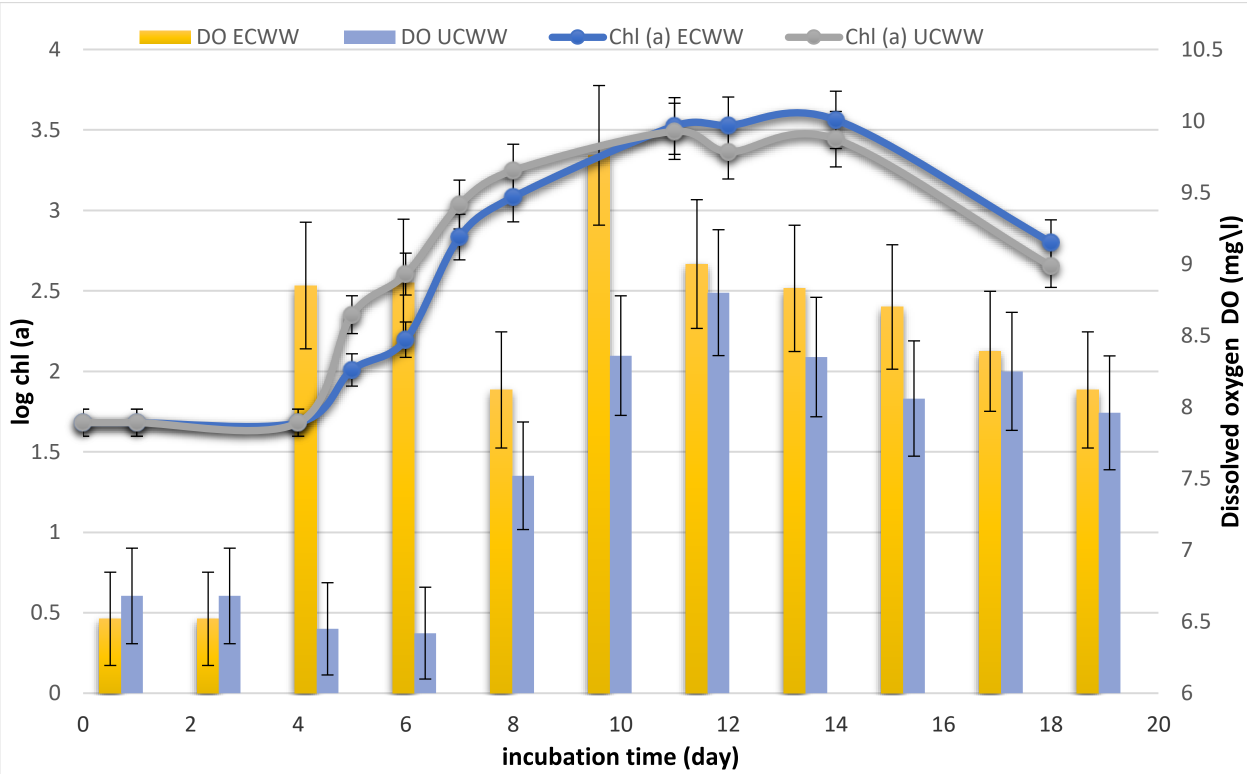

Fig. (1) Algal growth response and dissolved oxygen in the inoculated wastewater under coal smoke exposure

3.1.2. Algal growth response and CO_2 consumption

CO_2 levels were monitored during algal growth in wastewater samples at two-time points (Fig. 2): the 6th and 11th days, in both exposed (ECWW) and unexposed (UCWW) samples. The experiment demonstrated that algal growth in wastewater samples exhibited a positive response to coal smoke exposure, with slightly higher growth rates observed in exposed samples compared to unexposed samples, where the results indicated that CO_2 consumption exceeded 99% in both ECWW and UCWW samples at the early time point (6th day), with slightly higher consumption (99.6%) in the ECWW sample compared to the UCWW sample (99%). Additionally, CO_2 consumption rates were significantly high in both exposed and unexposed samples, exceeding 99% at both the 6th and 11th-day measurement points. These findings coordinate with a slightly higher growth rate in ECWW, which suggests that coal smoke exposure has a slightly positive impact on algal growth and CO_2 biofixation in wastewater treatment systems. These results indicate that coal smoke exposure may have a positive effect on algal-based wastewater treatment systems. The correlation between DO levels and growth optimization at 8.8 mg/L represents a crucial finding for process control. The exceptional CO_2 consumption rates (>99%) demonstrate the system's efficiency in carbon sequestration. These results exceed typical CO_2 fixation rates reported in conventional algal systems [29]. Also, this correlation between dissolved oxygen levels and growth performance aligns with studies by Dahai *et al.* (2024) [30], who identified similar optimal DO ranges for *Scenedesmus* species. This relationship highlights the importance of maintaining appropriate aeration in treatment systems. The enhanced CO_2 consumption in smoke-exposed samples (99.6%) suggests potential adaptation mechanisms that could be exploited for industrial applications. This aligns with findings by Dahai *et al.* (2024) [30], who documented similar CO_2 fixation improvements in adapted algal strains.

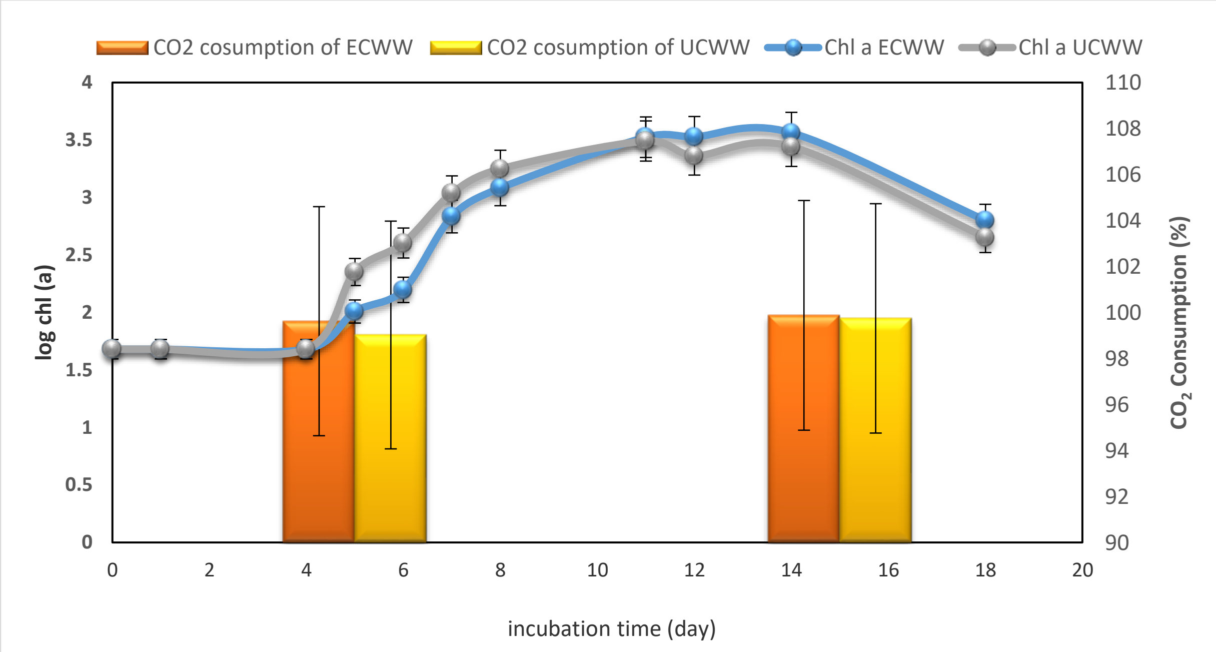

Figure (2) the growth response behavior and CO_2 biofixation

3.1.3. *Algal growth response and nutrient consumption*

Nutrient consumption, including nitrogen consumption (NO_3-N, NO_2-N, and NH_3-N) Figure (3) and phosphorus consumption (PO_4-P) Figure (4), serves as an indicator of the bioremediation efficiency achieved by microalgae in wastewater treatment systems. To assess the impact of coal smoke exposure on nutrient consumption efficiency, the bioremediation system was investigated at different time intervals (5, 7, 12, and 17 days) throughout the incubation period. As depicted in Figure (3, NO_3-N and PO_4-P consumption rates reached 100% from the early time point until the end of the investigation period, indicating the complete removal of these nutrients. NO_2-N consumption exhibited 95% and 99.5% rates in exposed (ECWW) and unexposed (UCWW) conditions, respectively, after which it reached 100% by the end of the investigation period. NH_3-N consumption demonstrated slight fluctuations throughout the investigation period, increasing from 86.9% at the early time point to 97.5% at the end of the investigation period in the exposed sample. A subtle difference was observed between exposed and unexposed samples, with NH_3-N consumption reaching 97.5% and 97%, respectively, by the end of the investigation period. Interestingly, the data revealed that even during the early stages of microalgal growth, nutrient consumption rates were relatively high.

The complete removal of NO_3-N and PO_4-P, coupled with high efficiency in NO_2-N and NH_3-N removal, demonstrates the robust nutrient uptake capabilities of the system. The progressive improvement in NH3-N removal (86.9% to 97.5%) indicates potential metabolic adaptation over time.

These results surpass conventional biological treatment systems, as documented by Qv *et al.* (2023) [31], who reported typical removal efficiencies of 70-85% for similar nutrients. The enhanced performance could be attributed to the synergistic effects of smoke exposure on nutrient uptake mechanisms.

The observed nutrient removal patterns demonstrate the species' exceptional bioremediation capabilities. The complete removal of NO_3-N and PO_4-P corroborates the findings of Choi and Lee (2015) [32], who reported similar efficiency in municipal wastewater treatment. The gradual improvement in NH_3-N removal (86.9% to 97.5%) suggests progressive adaptation to elevated nitrogen loads, consistent with observations by Fallahi *et al.* (2021) [33].

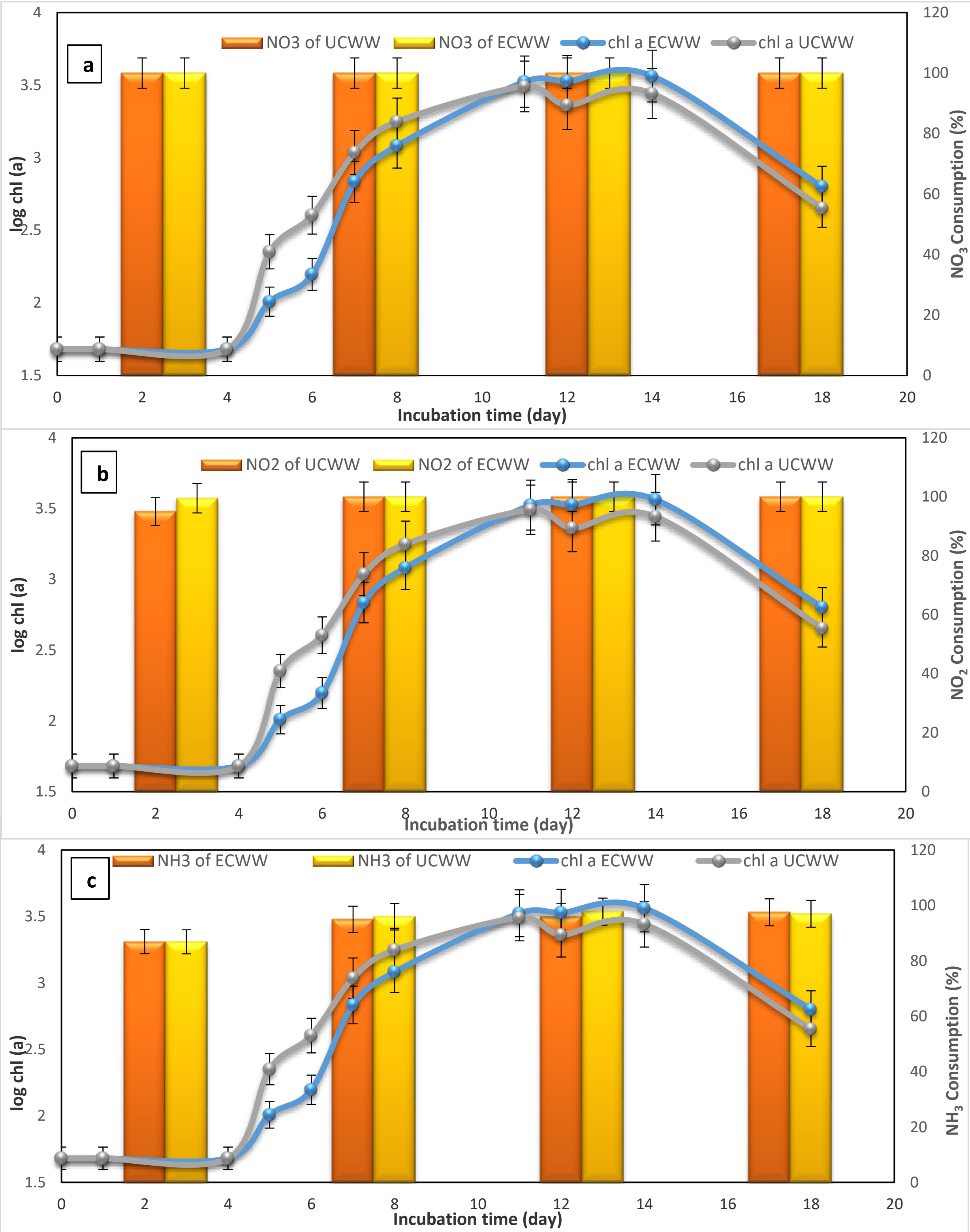

Figure (3) Algal growth response behavior and nitrogen (a: NO_3, b: NO_2, c: NH_3) uptake dynamic under the Coal smoke exposure

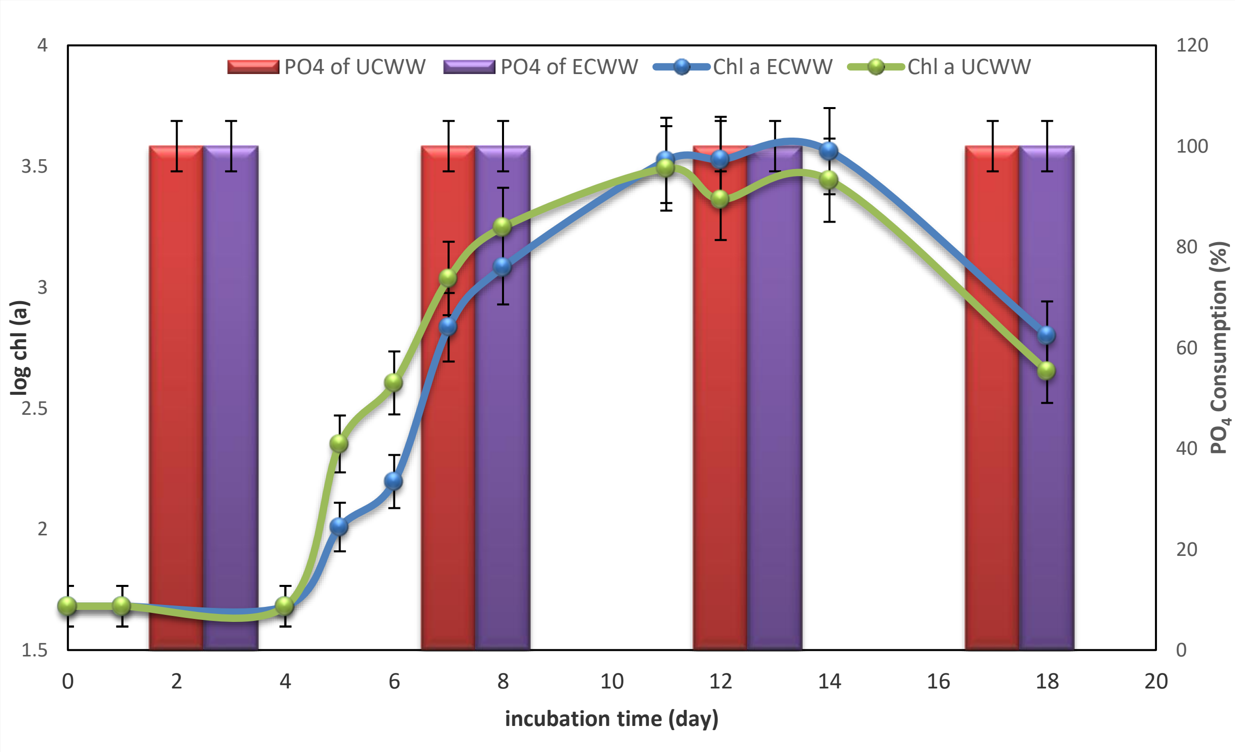

Figure (4) Algal growth response behavior and Phosphorous uptake dynamic under the Coal smoke exposure

3.2. The application of most optimum Factors on the Rice Straw smoke

The influence of rice straw smoke exposure on algal growth, nutrient uptake, and CO_2 biofixation was assessed by comparing the performance of a secondary treated wastewater sample inoculated with the most adapted isolated *Scenedesmus obliquus* strain in both exposed wastewater samples to Rice Straw smoke (ERSWW) and unexposed wastewater sample to Rice Straw smoke (URSWW) samples. The objective was to determine whether rice straw smoke exposure creates a favorable environment for algal growth.

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3.2.1. Algal growth response in the inoculated wastewater under the Rice Straw smoke exposure

The algae growth pattern in wastewater inoculated and exposed to rice straw smoke showed a clear trend, as depicted in Figure 5. In the first two days after inoculation, the algae exhibited a slow growth typical of the lag phase. Starting from the third day, growth accelerated rapidly and continued until the seventh day, marking the exponential growth phase. After this rapid increase, the algae experienced a brief two-day period of stable growth, followed by a short one-day exponential growth phase. Beginning on the tenth day, the algae again entered a two-day phase of steady growth. Growth started to decline after the fourteenth day. The sample exposed to rice straw smoke (ERSWW) reached its peak growth at 5588.11 µg/L chlorophyll (a) on day 14, which was slightly less than the maximum observed in the control. of the unexposed sample (URSWW), which reached a maximum of 6755.66 µg/L chlorophyll (a), the unexposed sample achieved its peak growth at a later stage (16^{th} day) compared to the ERSWW sample. Under analyzes the measured dissolved oxygen (DO) levels and their influence on algal growth in wastewater samples exposed and unexposed to rice straw smoke. Continuous monitoring of DO levels during algal growth revealed a direct and positive relationship between DO concentration and the growth rate of algae. As DO levels rose, a corresponding increase in algal growth was observed. This observation aligns with the established role of oxygen as a crucial factor for photosynthesis and consequently, algal growth. The data indicated that the maximum algal growth rates were attained at specific DO concentrations. In both wastewater conditions, peak growth occurred at a DO level of around 9.7 mg/L.

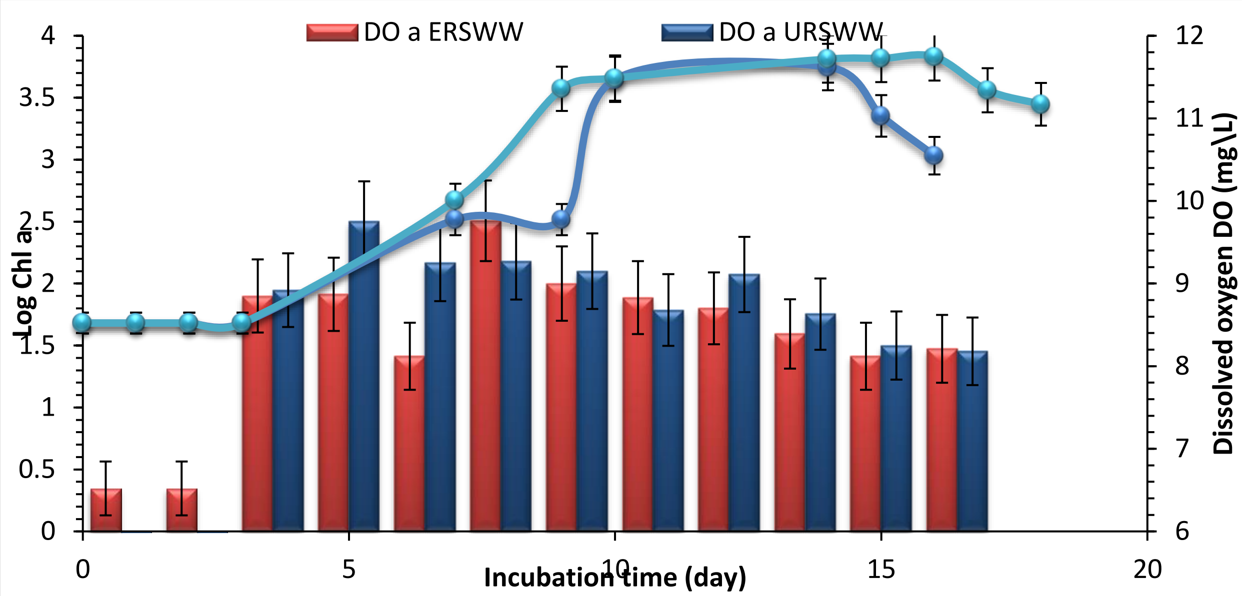

Figure (5) Algal growth behaviour and dissolved oxygen under the Rice Straw smoke exposure

3.2.2. *Algal growth response and CO_2 consumption*

CO_2 levels were monitored during algal growth in wastewater samples at three time points (Figure 6): the 2nd, 3rd, and 7th days, in both exposed (ERSWW) and unexposed (URSWW) samples. The experiment demonstrated that algal growth in wastewater samples exhibited a slightly positive response to rice straw smoke exposure. While exposed samples showed marginally lower growth rates compared to unexposed samples, the CO_2 consumption rates in exposed samples were consistently higher.

At the early time point (2nd day), the CO_2 consumption rate in ERSWW samples reached 96.9%, slightly higher than that of URSWW samples (92.4%). This rapid CO_2 consumption suggests enhanced algal metabolic activity under rice straw smoke exposure. At the subsequent time intervals, CO_2 consumption rates in ERSWW samples continued to increase, reaching 98.4% on the 3rd day and 100% on the 7th day. In contrast, CO_2 consumption rates in URSWW samples remained slightly lower throughout the experiment (96.8% on the 3rd day and 98.5% on the 7th day).

These findings suggest that rice straw smoke exposure may have a stimulatory effect on algal metabolic activity, leading to increased CO_2 uptake. However, the slightly lower growth rates observed in exposed samples indicate that rice straw smoke may exert some subtle effects on algal growth dynamics.

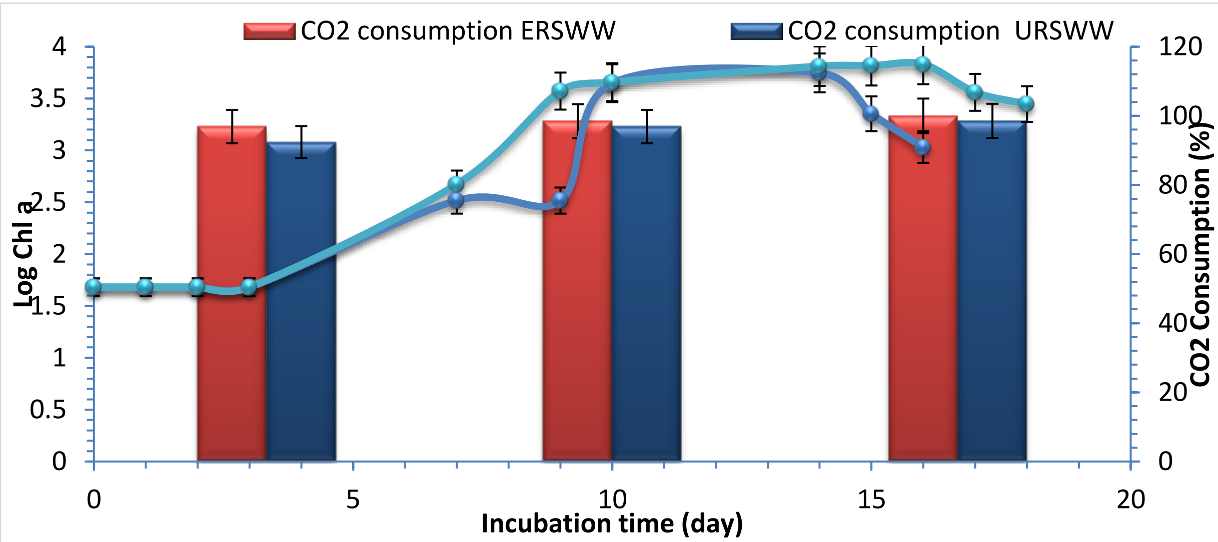

Figure (6) algal growth response behaviour and CO_2 biofixation under the Rice Straw smoke exposure

3.2.3. Algal growth response and nutrient consumption

Nutrient consumption, including nitrogen consumption (NO_3-N, NO_2-N, and NH_3-N) figure (7) and phosphorus consumption (PO_4-P) figure (8), serves as an indicator of the bioremediation efficiency achieved by microalgae in wastewater treatment systems. To evaluate the impact of rice straw smoke exposure on nutrient consumption efficiency, the bioremediation system was monitored at different time intervals (4, 9, 13, 17, and 21 days) throughout the incubation period .As depicted in Figure, NO_3-N, and PO_4-P consumption rates reached 100% from the initial time point until the end of the investigation period, indicating the complete removal of these nutrients. This rapid and efficient nutrient uptake highlights the remarkable bioremediation potential of microalgae .NO_2-N consumption exhibited 96.5% and 44.6% rates in exposed (ERSWW) and unexposed (URSWW) conditions, respectively, after which it reached 100% by the end of the investigation period. The lower initial NO_2-N consumption rate in the unexposed samples suggests a potential stimulatory effect of rice straw smoke exposure on NO_2-N removal .NH_3-N consumption also demonstrated high values at the early time point, with 98.1% and 96.5% rates in exposed (ERSWW) and unexposed (URSWW) conditions, respectively. NH_3-N consumption rates remained consistently high throughout the investigation period, reaching 100% by the end . Interestingly, the data revealed that even during the early stages of microalgal growth, nutrient consumption rates were relatively high. This suggests that microalgae possess an inherent capacity for efficient nutrient uptake, even under conditions of limited growth.

The observed differences in the growth patterns between the exposed and unexposed samples suggest that the rice straw smoke may have influenced the metabolic pathways or oxygen requirements of the algae [34]. The lower optimal DO concentration required for peak growth in the ERSWW samples could be attributed to the presence of components in the rice straw smoke that alter the algal physiology [35].

The enhanced CO_2 consumption rates in the ERSWW samples indicate that the rice straw smoke exposure may have a stimulatory effect on the algal metabolic activity, leading to increased CO_2 uptake [36]. This finding aligns with the concept of using microalgae for CO_2 biofixation in various industrial applications [37].

The remarkable bioremediation potential of the microalgae, as demonstrated by the high nutrient consumption rates, highlights their suitability for wastewater treatment applications [38]. The potential stimulatory effect of rice straw smoke exposure on specific nutrient removal, such as NO_2-N, suggests that the smoke components may have influenced the algal metabolic pathways involved in nutrient uptake [39].

Overall, the results of this impact contribute to the understanding of the interactions between rice straw smoke exposure and the growth, nutrient uptake, and CO_2 bio-fixation capabilities of the microalgae *Scenedesmus obliquus* in a wastewater treatment context.

3.3. The application of most optimum Factors on the petroleum smoke

The effects of petroleum smoke exposure on algal growth, nutrient uptake, and CO_2 biofixation were evaluated by comparing the performance of a secondary treated wastewater sample inoculated with the most adapted isolated *Scenedesmus obliquus* strain under both exposed wastewater samples to the petroleum smoke (EPSWW) and unexposed (UPSWW) conditions. The primary objective was to determine whether petroleum smoke exposure creates a favorable environment for algal growth.

3.3.1. Algal growth response in the inoculated wastewater under the petroleum smoke exposure

The growth pattern of algae in inoculated wastewater under petroleum smoke exposure exhibited a unique pattern, as illustrated in Figure 9. During the initial day of inoculation, the algal sample displayed a slow growth rate, characteristic of the lag phase. However, from the second day onwards, algal growth fluctuated between rapid and slow phases, continuing until the seventh day. This period of fluctuating growth represents the exponential phase. Following this phase, the algae entered a brief three-day period of steady growth. After the tenth day, algal growth began to decline.

Both petroleum smoke-exposed (EPSWW) and unexposed (UPSWW) samples exhibited maximum chlorophyll-a concentrations of 4407.5 µg/L and 4714.4 µg/L, respectively, on the tenth day. While the maximum growth in the exposed sample was marginally lower than that of the unexposed sample, both samples exhibited substantial growth potential .To analyze the influence of dissolved oxygen (DO) levels on algal growth in both exposed and unexposed wastewater samples (Figure 9), continuous monitoring of DO levels was conducted throughout the experiment. The results revealed a direct and positive correlation between DO concentration and algal growth rate. As DO levels increased, a corresponding increase in algal growth was observed. This observation aligns with the established role of oxygen as a crucial factor for photosynthesis and, consequently, algal growth.

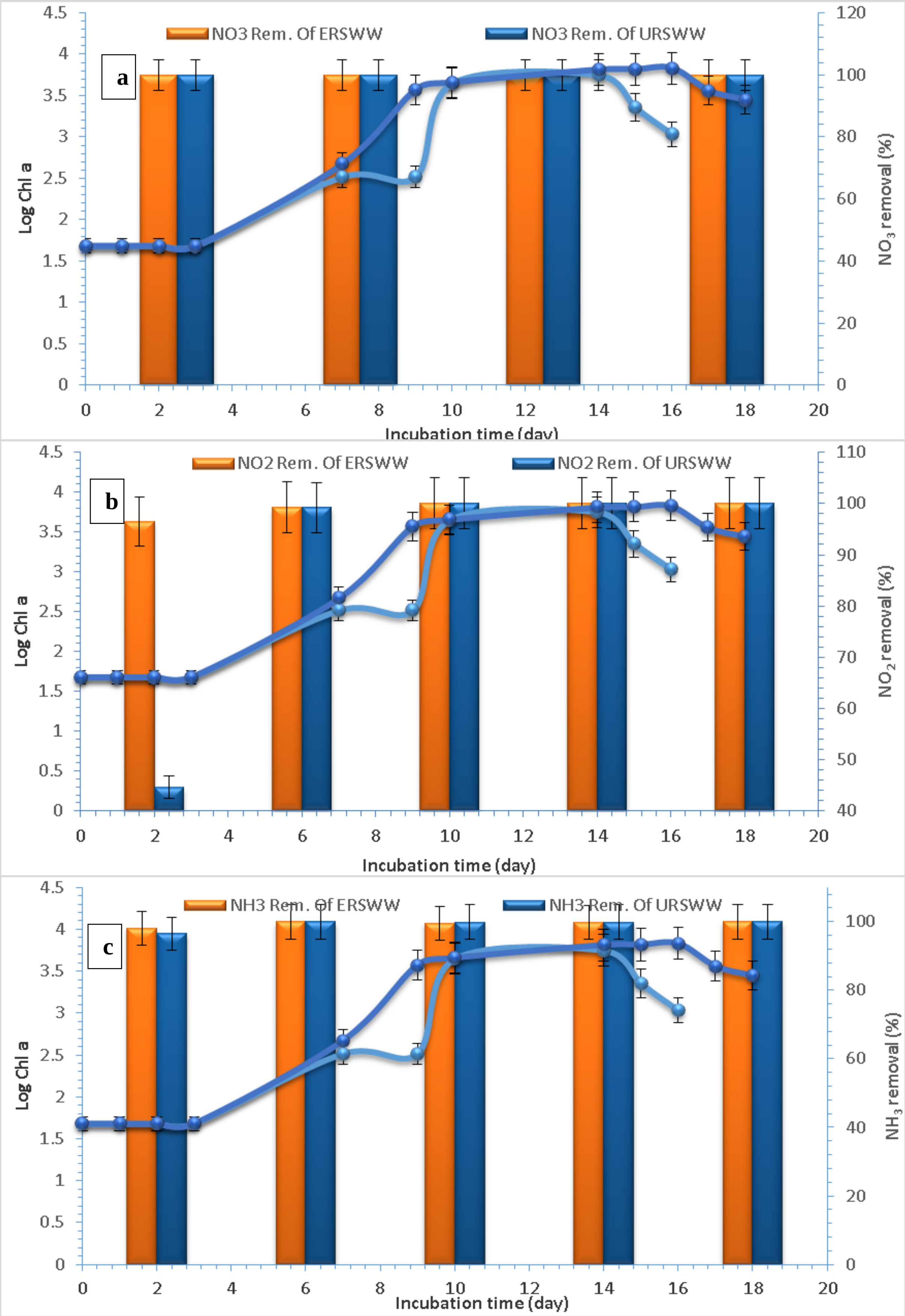

Figure (7) Algal growth response behavior and nitrogen (a: NO_3, b: NO_2, c: NH_3) uptake dynamic under the Rice Straw smoke exposure

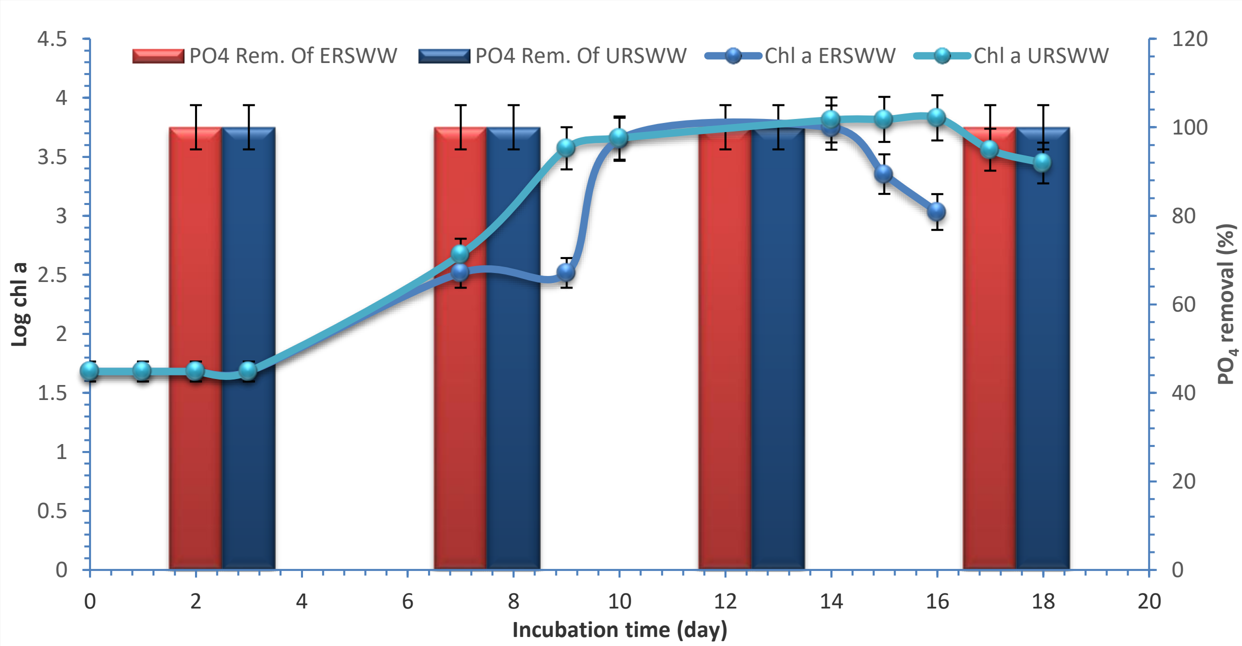

Figure (8) Algal growth response behaviour and phosphorus uptake dynamic under the Rice Straw smoke exposure

The data indicated that the maximum algal growth rates were achieved at specific DO concentrations. In unexposed wastewater samples (URSWW), peak growth occurred at a DO level of approximately 9.1 mg/L, while in the petroleum smoke-exposed wastewater samples (ERSWW), the optimal DO concentration for peak growth was around 9.4 mg/L. no significant difference between optimal DO levels for algal growth between EPSWW and UPSWW samples support the margin difference in chlorophyll-a concentrations.

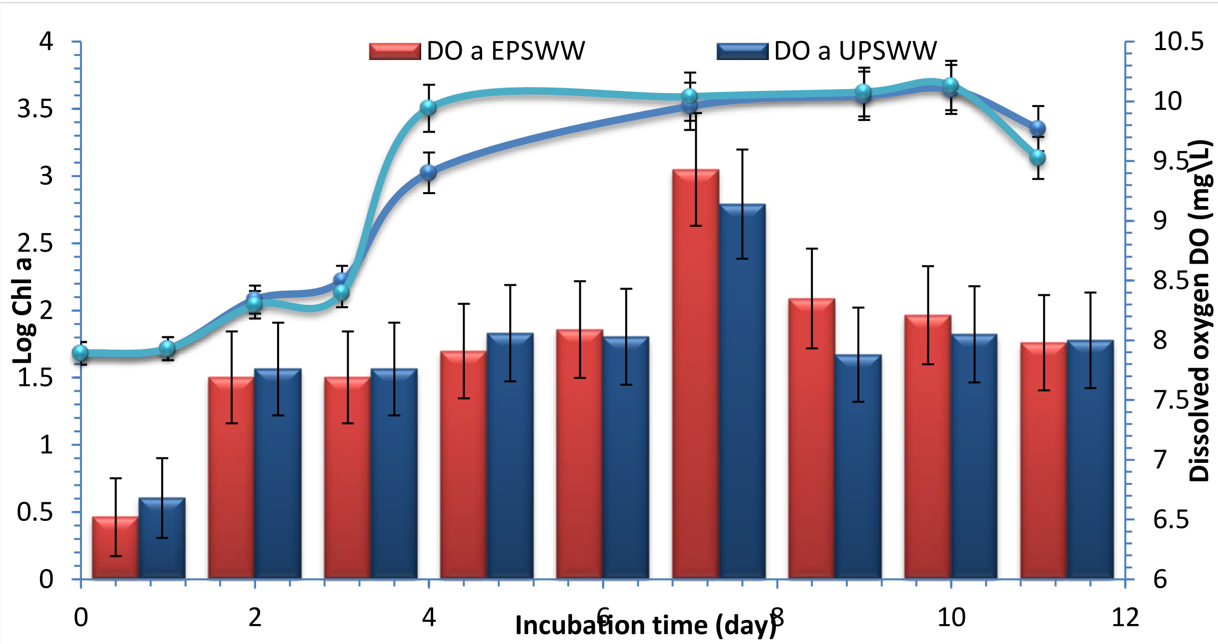

Figure (9) algal growth response and dissolved oxygen under the petroleum smoke exposure

3.3.2. Algal growth response and CO_2 consumption

CO_2 levels were monitored during algal growth in wastewater samples at four-time points (Figure 10): the 2^{nd}, 4^{th}, 7^{th}, and 9^{th} days, in both exposed (EPSWW) and unexposed (UPSWW) samples. The CO_2 consumption rates in both exposed and unexposed samples demonstrated rapid and efficient uptake, reaching approximately

99% at the early time point (2nd day) .Throughout the subsequent time intervals, CO_2 consumption rates in EPSWW samples remained consistent at around 99%, indicating sustained algal metabolic activity under petroleum smoke exposure. Similarly, CO_2 consumption rates in UPSWW samples continued at high levels, with no significant difference observed between exposed and unexposed samples .These findings suggest that petroleum smoke exposure does not exert any noticeable influence on algal metabolic activity or CO_2 biofixation. The observed high CO_2 consumption rates in both exposed and unexposed samples can be primarily attributed to the presence of the adapted *Scenedesmus* sps. Strain, which demonstrated a remarkable capacity for CO_2 uptake.

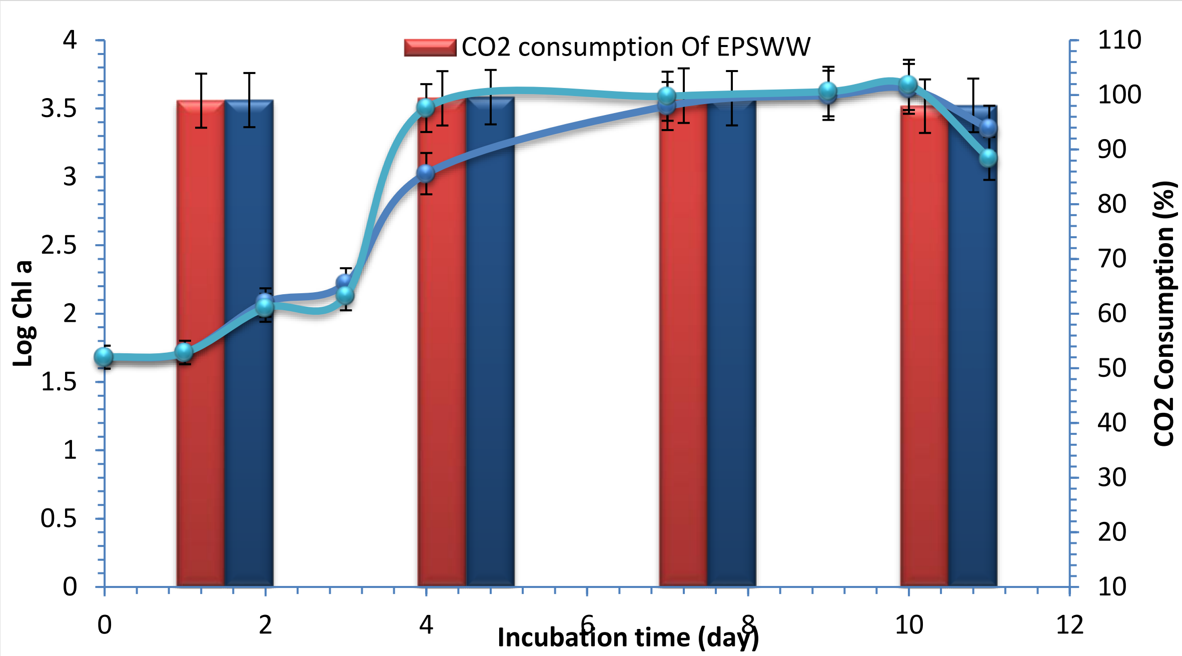

Figure (10) algal growth response behavior and CO_2 biofixation under the petroleum smoke exposure

3.3.3. Algal growth response and nutrient consumption

As depicted in Figures (11 and 12), NO_3-N, NO_2-N, and PO_4-P consumption rates reached 100% from the initial time point until the end of the investigation period, indicating complete removal of these nutrients. This rapid and efficient nutrient uptake highlights the remarkable bioremediation potential of microalgae, demonstrating their ability to effectively treat wastewater.

NH_3-N consumption demonstrated an intriguing pattern. In unexposed (UPSWW) conditions, NH_3-N consumption achieved high values at the early time point, reaching 98.9%. This high initial consumption suggests a rapid response of the microalgae to NH_3-N uptake. NH_3-N consumption rates in unexposed (UPSWW) conditions remained consistently high throughout the investigation period, reaching 100% by the end. In contrast, NH_3-N consumption in exposed (EPSWW) conditions showed a different pattern. Initially, NH_3-N consumption was relatively low, reaching only 22.3% at the early time point. However, over time, NH_3-N consumption rates in exposed samples demonstrated a significant increase, eventually reaching 66.9% by the 7th day and 99.6% by the end of the investigation period.

These findings suggest that petroleum smoke exposure may initially have a subtle inhibitory effect on NH_3-N uptake. However, microalgae appear to adapt to smoke exposure over time, eventually regaining their ability to efficiently consume NH_3-N. This indicates that while petroleum smoke exposure may have some transient effects on nutrient uptake dynamics, it does not significantly impair the overall bioremediation efficiency of microalgae.

This finding provides compelling evidence regarding the adaptability and efficiency of *Scenedesmus obliquus* in wastewater treatment systems under petroleum smoke exposure conditions. The results demonstrate several significant findings that contribute to our understanding of microalgal-based bioremediation systems in industrial settings.

The growth pattern of S. *obliquus* exhibited a characteristic biphasic response under petroleum smoke exposure, with distinct rapid and slow growth phases during the exponential period. Maximum chlorophyll-a concentration reached 4407.5 µg/L in exposed samples (EPSWW) compared to 4714.4 µg/L in control samples

(UPSWW) by day 10. This relatively small difference (approximately 6.5%) in maximum biomass production suggests the remarkable resilience of the strain to smoke exposure. These findings align with research by Wang et al. (2021) [40], who reported similar adaptive responses in Chlorella species exposed to industrial pollutants [40].

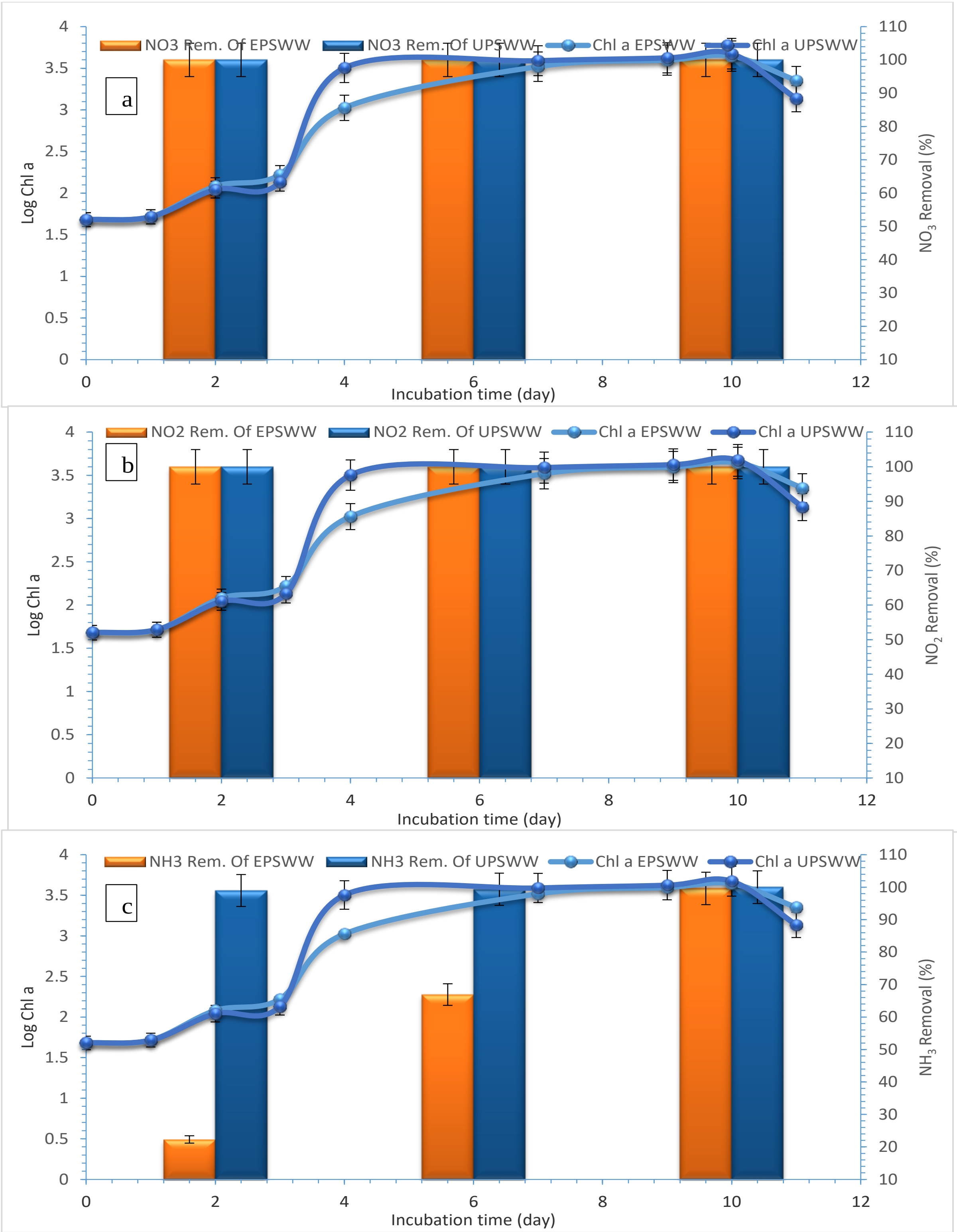

Figure (11) Algal growth response behavior and nitrogen (a: NO_3, b: NO_2, c: NH_3) uptake dynamic under the petroleum smoke exposure

The findings revealed optimal dissolved oxygen (DO) concentrations of 9.1 mg/L and 9.4 mg/L in unexposed and exposed samples, respectively. This slight elevation in optimal DO levels under smoke exposure suggests a metabolic adaptation mechanism, possibly related to enhanced oxygen demand for pollutant degradation. These results correspond with findings by Wang et al. (2021) [40], who documented increased oxygen requirements in microalgae under stress conditions.

A particularly noteworthy finding was the maintenance of high CO_2 consumption rates (approximately 99%) from day 2 onwards in both exposed and unexposed conditions. This efficient CO_2 fixation capacity, even under smoke exposure, supports the findings of A. Kumar et al. (2010) [41], demonstrated the robust carbon fixation abilities of *Scenedesmus* species under various stress conditions. The sustained CO_2 fixation efficiency suggests potential applications in combined wastewater treatment and carbon capture systems.

The finding revealed complex nutrient removal patterns: 1) at Nitrogen Species, where complete removal (100%) of NO_3-N and NO_2-N was achieved in both conditions, but NH_3-N removal showed a distinct pattern in exposed samples, Initial removal rate: 22.3% (significantly lower than control), Day 7: 66.9% removal, then Final removal: 99.6%, So that This delayed but eventual recovery in NH3-N removal efficiency suggests an adaptive response mechanism, similar to observations by X. Xiao (2023) [42] in their studies of microalgal adaptation to industrial pollutants. 2) at Phosphorus Removal, the consistent PO_4-P removal efficiency across both conditions indicates that phosphorus uptake mechanisms remain largely unaffected by smoke exposure. This aligns with research by Schmidt, and Jamieson (2016) [43], who documented the stability of phosphorus uptake pathways in microalgae under various stress conditions.

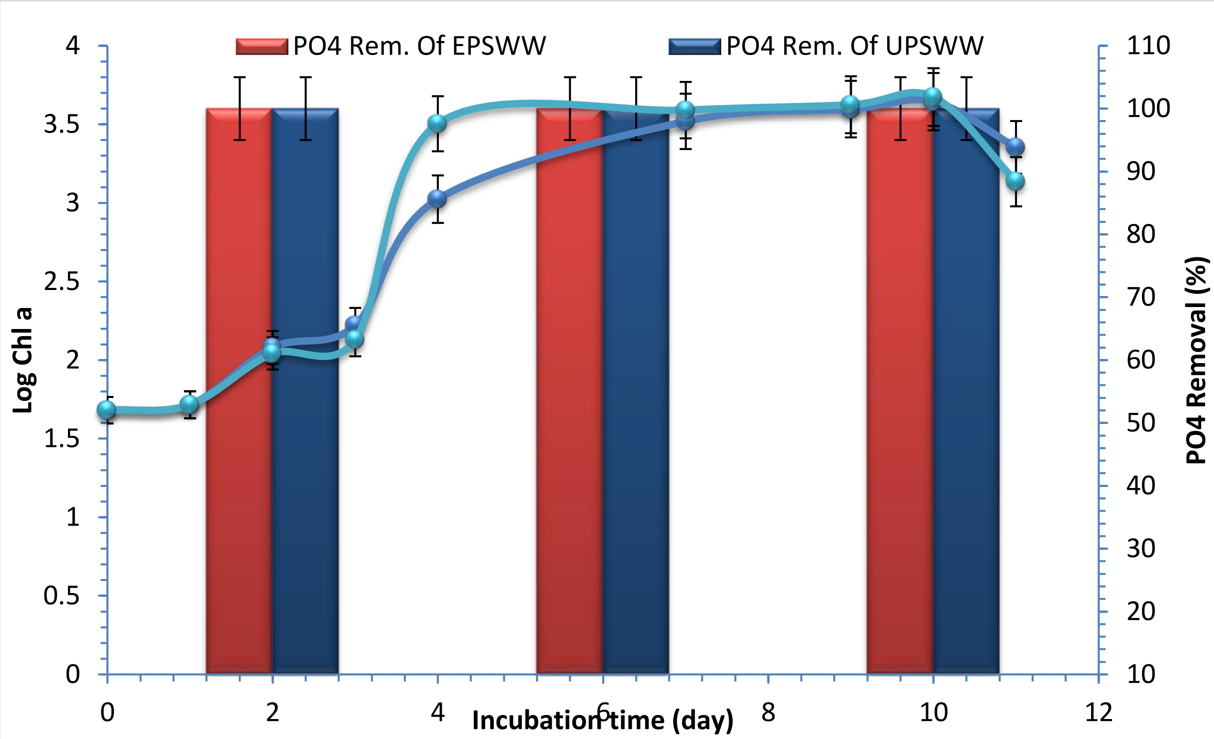

Figure (12) Algal growth response behavior and phosphorus uptake dynamic under the petroleum smoke exposure

4. Conclusion

This study demonstrated the significant effects of simulated industrial smoke on the growth, nutrient uptake, and CO_2 biofixation of the microalgal strain *Scenedesmus obliquus*. The findings indicate that different types of smoke—coal, rice straw, and petroleum—have varied impacts on algal performance in secondary treated wastewater.

Exposure to rice straw smoke yielded the highest biomass production and nutrient removal efficiency, highlighting its potential as a beneficial additive in wastewater treatment systems. Coal smoke also contributed positively, enhancing algal growth, although to a lesser extent. Conversely, petroleum smoke exhibited minimal effects, suggesting that S. *obliquus* possesses inherent tolerance to petroleum-derived pollutants.

The study underscores the adaptability of S. *obliquus* in contaminated environments, reinforcing its potential role in sustainable wastewater management and CO_2 mitigation. The observed correlations between algal growth, dissolved oxygen levels, and nutrient consumption rates emphasize the importance of environmental conditions in optimizing microalgal bioremediation processes. Overall, these results contribute valuable insights into the application of microalgae for industrial wastewater treatment, presenting opportunities for further research and practical implementation in environmental management strategies.

5. Conflicts of interest

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

6. Funding

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