Hindawi
Advances in Civil Engineering
Volume 2024, Article ID 8564202, 17 pages
https://doi.org/10.1155/2024/8564202

Research Article

Exploring the Potential of Green Microalgae-Based Phycoremediation Treated Wastewater for Sustainable Concrete Production

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Received 20 October 2023; Revised 31 January 2024; Accepted 21 February 2024; Published 28 February 2024

Academic Editor: Isaac I. Akinwumi

Wastewater pollution from domestic, industrial, and agricultural sources threatens the environment and human health. Traditional wastewater treatment methods are energy intensive, generate significant sludge, and may not remove all contaminants. This study explores the use of microalgae, *Chlorella sorokinianana*, to treat wastewater and evaluates its impact on concrete properties. The research aims to optimize microalgae growth conditions, set up nutrient-rich growth chambers, develop biomass separation methods, and assess the effects of microalgae-treated wastewater on concrete. Scanning electron microscopy (SEM) was used to analyze concrete structures produced with microalgae-treated wastewater, freshwater, and sewage treatment plant (STP) water. Concrete from microalgae-treated wastewater exhibited euhedral crystals with pronounced gaps, while freshwater concrete had denser subhedral to anhedral crystals. STP water concrete consistently had lower strength values, possibly due to impurities affecting cement hydration. Microalgae-treated water concrete showed intermediate strength levels, suggesting organic or biological factors may influence hydration, but it still gained strength with time. This study underscores the potential of microalgae-treated wastewater for sustainable concrete production, highlighting the importance of further research to optimize conditions and promote environmentally friendly construction practices.

1. Introduction

Pollution due to wastewater from domestic, industrial, and agricultural activities is a significant environmental issue that harms the ecological balance and poses a treat to human health. Wastewater contains various contaminants, and heavy metals, organic matter which when left untreated or improperly treated and discarded into natural waterbodies lead to eutrophication, oxygen depletion, and accumulation of toxic substances.

The conventional method of wastewater treatment is energy intensive and produces a large amounts of sludge and by-products. Moreover, they do not remove all contaminants and such pollutants can be harmful to both the environment and human health [1]. The requirement for a natural and sustainable means to treat wastewater and its advantages have been studied in the past decades [2]. Phycoremediation is one such process which utilizes green algae due to its high adaptability and rapid growth in various environmental conditions along with its sustainable and cost-effective approach. Green algae also have the advantage of being able to tolerate high levels of pollutants and remove many contaminants such as phosphorous, nitrogen, heavy metals, and organic compounds. Their rapid growth in nitrogen and phosphorus-rich water positions them as key contributors to eutrophication and algal blooms, making them highly effective agents in the removal of nitrogen and phosphorus from such environments. The process of photosynthesis is accomplished by green algae to consume the contaminants and nutrients in the wastewater to produce biomass and oxygen. It also poses an advantage of requirements of lower energy, reduced chemical usage and production of biofuels and other valuable by-products. Decentralized wastewater treatment systems are also an absolute necessity in small villages and areas which

have lower wastewater output, and this method can be implemented in such small scaled requirements as well. Phycoremediation can play a pivotal role in safeguarding water resources by diminishing the burden on wastewater treatment facilities, enhancing their effectiveness, and harnessing the potential for reusing effluent. Another benefit of employing microalgae in wastewater remediation is the high-value molecules present in the produced algal biomass [3]. These molecules can be further refined for utilization across various industrial sectors, including biofuel production, animal feed, and fertilizer production. The utilization of microalgae is expected to become increasingly essential in advancing both wastewater treatment methodologies and the efficient reuse of reclaimed wastewater.

Selecting the appropriate species of algae is of utmost importance for the effective treatment of wastewater. This is because both municipal and industrial wastewaters can vary in terms of nitrogen and phosphorus concentrations, light availability, and metal content, all of which may not be conducive to the growth of all algal species. Microalgae organisms have different strategies when exposed to pollutants, with some unable to adapt to increased nutrient levels, while others may exhibit rapid growth in such conditions. Regrettably, there has been a limited number of studies that utilize native microalgae cultures as opposed to laboratory-grown pure culture strains as observed in Almomani and Örmeci's research. Consequently, there is a continued need to search for novel microalgal strains that can exhibit robust growth in wastewater, thus enabling highly efficient wastewater treatment. It is worth noting that this study appears to be among the first to explore the use of diatom Veneta in phytoremediation efforts. Additionally, the current understanding of growth rates, biomass performance, and their correlation with nutrient removal efficiency relies heavily on intricate and time-consuming analyses, including cell counting and in vitro pigment assessment. Consequently, isolating microalgae species directly from wastewater or polluted environments can offer distinct advantages. These isolated strains are already acclimated to the biotic and abiotic stresses present in the medium, leading to higher nutrient removal efficiency. However, there remains a gap in our understanding regarding the performance of different strains of microalgae in wastewater treatment, which warrants further research and exploration.

The demand for freshwater in the construction industry is substantial, considering that only 3% of the Earth's water is freshwater, with the remaining 97% being saltwater in oceans. Among the freshwater resources, only 1% is readily available as surface water or groundwater, while the majority is locked in polar ice caps. As the global population continues to grow, there is an increasingly urgent need for alternative water sources to meet the demands of industries that rely on freshwater [4]. One promising alternative is treated wastewater, which is abundant and has the potential to fulfill the water requirements of various industries. Recycled water involves the process of reclaiming water from different sources, treating it, and reusing it for purposes such as irrigation and groundwater replenishment [5]. Despite its wide range of applications, the use of recycled water is somewhat limited due to residual chemicals, a faint yellowish color, and odor that may still be present in the treated water. To address these issues, we are exploring the use of microalgae to treat wastewater from sewage treatment plants (STPs) with the aim of removing these residuals.

In a study conducted by Pathak et.al. [6] in 2014, the primary objective was to utilize *Chlorella pyrenoidosa* microalgae for the purification of textile wastewater. The research included a time-dependent experiment to assess the dye removal capacity of dried algal biomass. The findings indicated that the highest level of color removal occurred approximately 30 min after introducing the dried algal biomass to different concentrations of simulated textile wastewater containing methylene blue (MB) dye [7]. In the study conducted on Gani [8], it was found that *Botryococcus* sp. had the capability to significantly reduce various parameters in dairy effluent. This included a reduction of 73.3% in BOD, 65.1% in TOC, 61.4% in TC, 58.3% in IC, and 48.8% in COD when applied to 100% concentration of the effluent [8]. In the research conducted by Kumar [9], the use of sewage wastewater led to enhanced biomass productivity when compared to standard batch cultivation methods. Continuous flue gas feeding plays a crucial role in supporting the growth of microalgae by supplying essential nutrients such as carbon, nitrogen, and sulfur [9]. The study demonstrated that the highest biomass yield was achieved through a mixotrophic, heterotrophic batch cultivation approach. Notably, the treatment also resulted in the removal of nutrients and pollutants, reaching up to 80% removal from the sampled wastewater. In a recent study conducted by Kemal Simsek, the research focused on evaluating the efficacy of the native green microalgae *Golenkinia radiata* Chodat, 1984 (Chlorophyceae, Chlorophyta) in removing N, P, and COD from municipal wastewater [10]. The study's findings suggest that this microalgae species could potentially serve as a robust candidate for both wastewater treatment and the production of biomass from wastewater, based on the obtained results. In a study conducted by Khan et al. [11], it was observed that *C. glomerata* exhibited superior efficiency in removing heavy metals (Cd and Pb) compared to *V. debaryana* [11]. Consequently, it can be concluded that phycoremediation is a cost-effective and environmentally friendly technique suitable for remediating industrial effluents contaminated with these heavy metals.

Meena and Luhar's study investigated the use of different waste effluents in mixing and curing concrete, namely, tertiary treated waste effluent, secondary treated waste effluent, and normal tap water (TW) for control purposes. They assessed the workability of the concrete mixes through a slump test following 1199-1959 guidelines and found that the concrete mixed with waste effluent had lower slump values compared to the control mix with TW. This reduction in workability was attributed to the solid content in the waste effluents, which had a spongy texture and high water absorption capacity. The samples' compressive strength was assessed following 7, 28, and 90 days of curing. The results indicated that the compressive strength of the waste effluent samples was inferior when compared to the samples mixed with drinkable water. This decline in strength was linked to the existence of ettringites, which transformed into substances like monosulfate aluminate and subsequently dissolved during the hydration

process [12]. In the study conducted by Noruzman et al. [13], researchers employed wastewater from three distinct origins: STP effluent, palm oil mill effluent, and heavy industry effluent. The investigation consistently demonstrated an increase in the setting time for all concrete blends that incorporated these wastewater sources. Notably, the mixture containing effluent from palm oil treatment displayed the lengthiest setting time, which was attributed to the presence of organic contaminants in the effluent. Similarly, the combinations using treated effluent from heavy industry and domestic sewage also exhibited extended setting times when compared to the mixture made with potable water [13]. In their study, Al-jabri et al. [14] employed wastewater from a car wash station for both the mixing and curing processes of the concrete matrix. They conducted compressive strength tests on 150 mm cubes after 7 and 28 days. The findings indicated that the strength of the concrete samples mixed with waste effluent was lower compared to those mixed with TW. Specifically, the 7-day and 28-day strengths of the TW concrete were 66 and 77 MPa, respectively, which were higher than the corresponding strengths of 63.8 and 72 MPa for the wastewater concrete [14].

In general, the utilization of waste effluents in cement and concrete production presents opportunities for sustainable development. Nevertheless, it is essential to take into account the unique attributes of these effluents and their impact on the intended qualities of cement and concrete. Additional research is required to fine-tune the incorporation of waste effluents and ensure they align with construction standards and specifications. The study on the utilization of microalgae for wastewater treatment is expected to become increasingly essential in advancing both wastewater treatment methodologies and the efficient reuse of reclaimed wastewater [15].

The use of algae-treated wastewater in concrete production aligns with broader sustainability goals and initiatives in the construction industry in several ways. This practice can contribute to environmental, social, and economic sustainability by addressing water resource management, reducing environmental impact, and providing economic benefits. The key considerations include water conservation initiatives, aligned with SDG 6, play a crucial role in reducing freshwater demand, particularly in water-scarce regions, with potential economic benefits through cost savings in freshwater acquisition for concrete mixing. Nutrient recycling, associated with SDG 12, contributes to mitigating nutrient pollution in water bodies, though specific economic implications are not specified. Carbon footprint reduction efforts, in line with SDG 13, may lower the environmental impact of treatment processes, yet economic implications are not explicitly outlined. Embracing circular economy principles aligns with SDG 12, promoting resource efficiency, and potential cost savings in concrete production. Economic viability and cost savings, aligned with SDG 6, require further exploration to assess feasibility considering treatment and cultivation expenses. Social impacts, aligned with SDGs 3, 10, 16, and 17, highlight the need for community engagement and education to ensure broader social acceptance. Regulatory compliance with water quality standards (SDG 6) is essential to avoid fines or increased costs. Long-term resilience efforts, aligned with SDGs 9, 11, and 17, can yield economic benefits by mitigating risks associated with water scarcity or regulatory changes, though specific environmental impacts are not detailed. However, further exploration is needed to assess economic implications, taking into account treatment costs, resource availability, and potential cost savings. Collaborative efforts among industry stakeholders, researchers, and policymakers are essential for advancing sustainable practices in construction.

In terms of its environmental impact and sustainability with traditional wastewater treatment methods, wastewater undergoes a multistep treatment process to ensure its safe discharge into the environment. Initially, large debris is removed through screening. In primary treatment, settleable solids are separated by allowing the wastewater to settle in tanks. Secondary treatment involves biological processes, like the activated sludge method, trickling filters, and rotating biological contactors, which break down organic matter. Tertiary treatment further polishes the water through methods such as filtration and chemical treatment. Disinfection using chlorination or UV light targets pathogens. Finally, sludge treatment manages solid residues through anaerobic digestion, dewatering, and disposal methods like incineration or landfilling. This comprehensive approach ensures the effective removal of pollutants, yielding treated water that meets environmental standards.

Phycoremediation, a method that utilizes microalgae or other photosynthetic organisms to treat wastewater, has been explored as an alternative to traditional wastewater treatment methods.

To compare the environmental impact and sustainability of phycoremediation with traditional methods, various metrics and analyses can be considered, as shown in Table 1.

The objectives of the study include:

(1) Optimizing the growth condition of microalgae such as temperature, pH, and light intensity to enhance their pollutant removal efficiency.
(2) Checking the effect of the algae-treated wastewater on the properties of concrete.

2. Materials and Methods

Microalgae, as photosynthetic phytoplanktonic organisms, play a crucial role in the aquatic ecosystem as they constitute the primary link in the food chain. Their ecological importance extends to their significant contributions to the carbon and silicon cycles. Remarkably, they are responsible for approximately 20%–25% of global carbon fixation through photosynthesis and account for an impressive 40% of global primary production [15]. While the treatment of green algae is a multimechanised system, one of the primary mechanisms is photosynthetic uptake. Here, the microalgae utilize carbon dioxide and nutrients in wastewater during photosynthesis, which in turn reduces the concentration of nutrients such as nitrogen and phosphorous, which are the main reasons for the process of eutrophication.

Table 1: Comparison of environmental impact and sustainability of phycoremediation with traditional methods with reference to standard guidelines.

Factor	Phycoremediation	Traditional methods	Standards/guidelines
Energy consumption	Lower energy consumption, especially with natural sunlight	Moderate to high energy consumption, e.g., aeration and pumping	ISO 14046:2014—energy intensity (kWh/m^3)
Chemical usage	Minimal or no chemical usage, relying on biological processes	Moderate to high chemical usage for coagulation, flocculation, etc.	ISO 14001:2015—chemical oxygen demand (COD) removal efficiency
Biosolids production	Can produce biomass for reuse (e.g., biofuel, fertilizer)	Generates biosolids requiring disposal, may need further treatment	EPA 40 CFR Part 503—biosolids quality standards
Land use	Can be implemented in open bonds or photobioreactors	Requires larger treatment facilities and more land	ISO 14040:2006—land use intensity (e.g., m^2/year)
Nutrient removal	Effective in removing nutrients like nitrogen and phosphorus	Can remove nutrients but may need additional processes	WEF nutrient removal manual—nutrient removal efficiency
Carbon footprint	Captures and utilizes CO_2, potentially sequestering it	May have a carbon-intensive footprint depending on energy use	ISO 14064-1:2018—CO_2 equivalent emissions
Water quality improvement	Enhances water quality, pollutant removal, oxygennation	Effective in pollutant removal but may have limitations in oxygenation	WHO guidelines for drinking—water quality
Cost considerations	Variable initial setup costs lower operational costs	Higher upfront and operational costs, depending on complexity	ISO 14007:2019—life cycle cost analysis

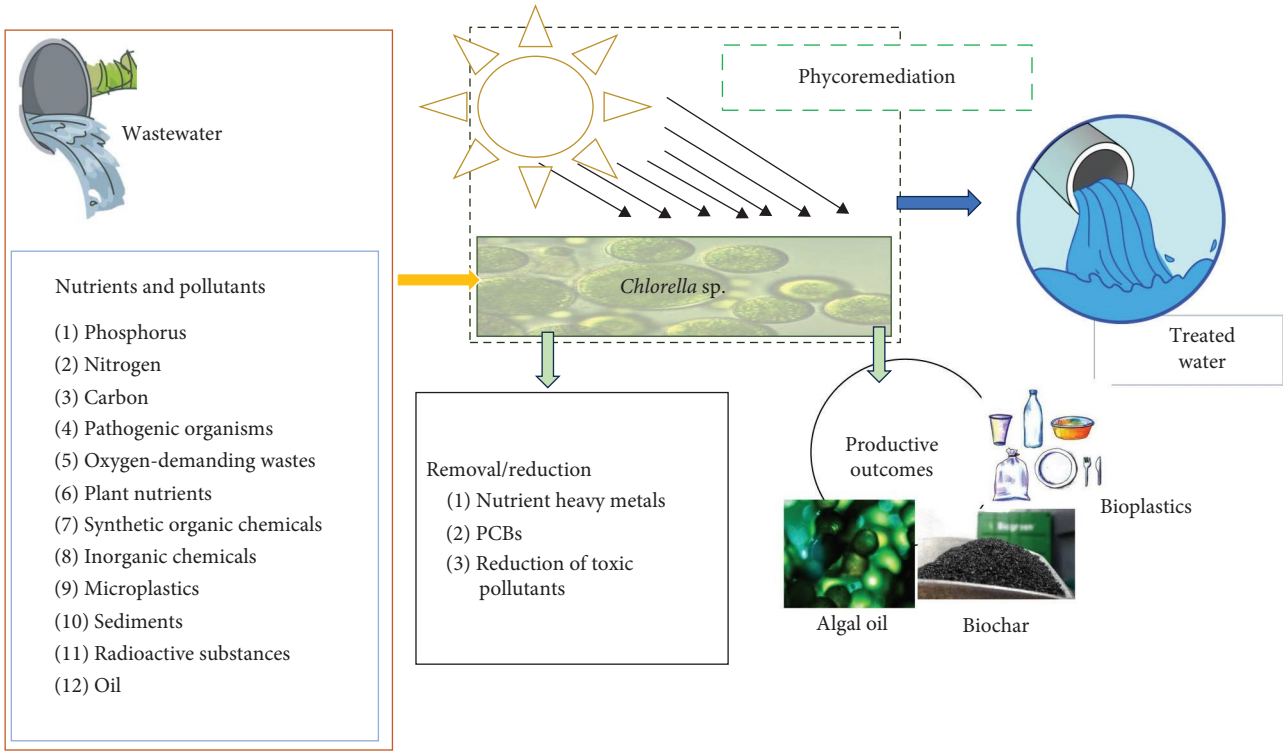

Figure 1: Process of phycoremediation.

Microalgae employ multiple mechanisms to eliminate pollutants from wastewater. The first mechanism involves adsorption, wherein pollutants in the wastewater adhere to the microalgae's surface. This is especially effective for removing heavy metals [16]. The second mechanism is precipitation, where microalgae convert pollutants into insoluble compounds, simplifying their removal from the wastewater. Lastly, there is assimilation, in which microalgae utilize nutrients in the wastewater to produce biomass, making it a potent method for removing nitrogen and phosphorus from wastewater [17]. Figure 1 depicts the process of phycoremediation where nutrients removal, heavy metals, and reduction of toxic pollutants can lead to the production of various by-products, such as biochar and algal oil.

Chlorella, a significant genus within the phylum Chlorophyta, plays a crucial role in biomass production and the synthesis of various biological compounds, such as lipids, proteins, carbohydrates, pigments, and vitamins [18]. Among the promising species within the genus *Chlorella*, *Chlorella sorokinianana* stands out for its ability to thrive under diverse conditions, including auto-, hetero-, and mixotrophic growth across a wide temperature range. This particular species holds great potential for the development of effective technologies in wastewater treatment [19].

The methods employed to accomplish the intended goals are as follows:

(a) The first approach involves bioprospecting for microalgae *Chlorella* sp. suitable for domestic wastewater treatment. Subsequently, laboratory-based analysis of water quality will be conducted to assess the suitability of algae-treated wastewater for concrete applications.

(b) The second method entails civil construction design engineering, where algae-treated wastewater will be tested to evaluate their effectiveness in facilitating the phycoremediation process for wastewater treatment and later used for mixing and curing process of preparation of concrete mix.

Culturing *Chlorella* sp. includes:

(1) Selection of strain: Choose a specific microalgae strain, like *Chlorella* sp., based on the intended application and environmental conditions. In this case, *Chlorella* sp. was considered suitable for domestic wastewater treatment.

(2) Inoculation and cultivation: Inoculate a suitable culture medium with the chosen microalgae strain. Bold's Basal medium is widely employed for the cultivation of various microalgae, including Chlorella. The basic formulation included nitrate or ammonium as nirogen source, phosphate as phosphorous source along with trace elements, such as iron, manganese, zinc and copper, and vitamins, such as thiamine and biotin. *Chlorella* sp. typically thrives in a slightly alkaline to neutral pH range (6.5–8.5). pH levels outside this range may impact nutrient availability and metabolic processes. Further, the temperature range for *Chlorella* sp. cultivation is typically between 20° and 30°. Also, the effect of light source should provide an appropriate spectrum with wavelength in blue and red regions for

Figure 2: STP water.

effective photosynthesis. Light–dark cycles (photoperiods) are also crucial with common cycle being 12 hr of light and 12 hr of darkness.

(3) Monitoring and control: Regular monitoring of the culture parameters, such as pH, temperature, nutrient levels, and light intensity, is an absolute requirement to optimize the microalgae growth.

Various harvesting techniques of *Chlorella* sp. include:

(1) Filtration: Separate the microalgae from the culture medium using various filters or centrifugation to concentrate the biomass.
(2) Flocculation: Induce flocculation, a process where microalgae aggregate, making it easier to separate them from the culture medium.
(3) Centrifugation: Use centrifugal force to separate microalgae cells from the liquid medium based on their density differences.

Microfilters, characterized by their fine pore sizes are used to effectively separate Chlorella cells from the culture medium. The application of either pressure facilitates the passage of the liquid medium through the microfilter, while the microalgae biomass is retained on the filter surface.

Dewatering is a postharvesting process where excess water is removed from concentrated microalgae biomass. In mechanical pressing, the concentrated Chlorella biomass is placed between pressing surfaces, and pressure is applied to squeeze out excess water.

The biomass dosage utilized in this case was in the ratio of 1 : 10 indicating the amount of Chlorella biomass (by weight) to the volume of wastewater treated. The biomass concentration considered was 1 g/l.

The study utilized secondary treated water (Figure 2) obtained from the STP at Jyothy Institute of Technology as the water source (Figure 3) for cultivating a proprietary *Chlorella* sp. (Figure 4) cultured and harvested as mentioned above by E2E Biotech Pvt. Ltd. Overall, the samples included

Figure 3: Sewage treatment plant.

Figure 4: Algae sample.

freshwater as control, STP water, and algae-treated STP water.

The STP water collected were treated after cultivation of the algal mass with a retention time, that is, the duration of contact between the biomass and wastewater of 14 days, as shown in Figure 5. The algae were then separated from the STP water using a basic filtration process (Figure 6) and were stored in containers for further testing (Figures 7 and 8). Similarly, the control sample and the STP water were also used to conduct basic tests on water quality and arrive at a comparison between them.

2.1. Microalgae's Growth Progress. There are many methods that can be deployed for measuring the algal growth like cell counting, chlorophyll estimation, dry/wet biomass weights, and packed cell volume.

To track the microalgae's (*Chlorella sorokiniana*) growth progress, optical density (OD) measurements of the algae-treated wastewater were taken at regular intervals, starting from the initial day and continuing until reaching the optimal growth stage. Growth parameters, including cell density, were assessed using a haemocytometer. Additionally, periodic examinations were conducted to check for potential

Figure 5: Algae water after 2 weeks.

Figure 6: Separating algae from STP water.

Figure 7: Treated STP water by algae.

Figure 8: Treated water for all tests.

Table 2: The measurement of optical density (OD) or absorbance at wavelength (660 nm) using a UV–visible spectrophotometer.

S. no.	Day	Absorbance at 660 nm
1	0	0.062
2	3	0.18
3	6	0.30
4	9	0.46
5	12	0.69
6	15	0.85

parasites growing in the algae-treated secondary wastewater through microscopic observations.

To track the growth, a 10 ml sample was collected every 3 days over a period of 15 days. The measurement of OD or absorbance was performed at a specific wavelength (660 nm) using a UV–visible spectrophotometer, specifically the Shimadzu UV-1700 PharmaSpec model.

Based on the data provided in Table 2, which shows the absorbance at 660 nm at different time points (days), we can draw the following conclusions about cell growth:

(1) Increase in absorbance: As the number of days increases, there is a consistent increase in absorbance at 660 nm. This suggests that there is an increase in the density or concentration of cells in the sample over time.

(2) Positive correlation: The absorbance values are positively correlated with the number of days. This correlation indicates that the cell population is likely growing or becoming more concentrated as time progresses.

(3) Exponential growth: The rate of increase in absorbance appears to be accelerating, especially between days 9 and 15. This pattern is indicative of exponential

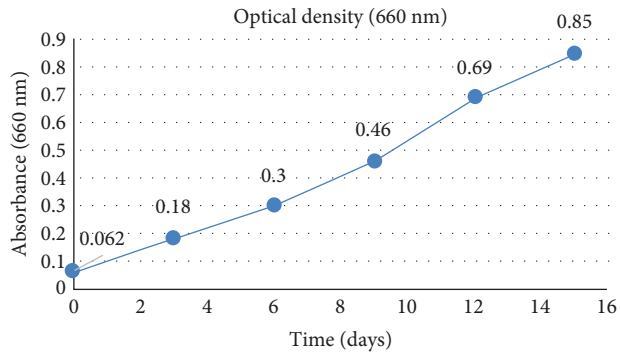

FIGURE 9: Graph depicting absorbance at 660 nm till 15 days.

TABLE 3: The cell density of *Chlorella* sp. on days 5,10, and 15.

Day	Number of cells (ml)
5	1.25×10^7
10	1.72×10^7
15	1.95×10^7

growth, which is characteristic of many cell populations when provided with suitable nutrients and conditions.

(4) Healthy cell growth: The steady increase in absorbance without decline suggests that the cell culture is likely healthy and not experiencing significant stress or cell death during the observed period.

While absorbance at 660 nm can be indicative of cell growth, it is important to note that this method provides a general measure of biomass or cell density. Additional analyses, such as cell counting with a haemocytometer or more specific assays, may be needed to confirm the nature of the cells and their health.

In summary, based on the provided absorbance data and as indicated in Figure 9, it appears that there is positive and likely exponential cell growth occurring in the culture over the 15-day period, indicating a healthy and actively proliferating cell population.

To determine the cell concentration, hemocytometry was employed. The haemocytometer consists of nine equally sized large squares, with the central square subdivided into 25 smaller squares, each having a volume of 4×10^{-6} ml. Cells were counted within these small squares as their effective diameters were less than 10 μm. The total cell count per milliliter was subsequently calculated as depicted in Table 3 and its microscopic view is depicted in Figure 10. Figure 11 presents the microscopic view of *Chlorella* sp. Furthermore, Figure 12 shows the magnified field of view of haemocytometer on day 15.

Growth over time: The cell density of *Chlorella* sp. increases over the 15-day period, indicating that the *Chlorella* sp. population is growing.

(1) Rate of growth: To determine the rate of growth, the difference in cell density between day 10 and day 5, as well as between day 15 and day 10 was calculated:

Growth from day 5 to day 10 : $1.72 \times 10^7 – 1.25 \times 10^7 = 0.47 \times 10^7$ cells/ml.

Growth from day 10 to day 15 : $1.95 \times 10^7 – 1.72 \times 10^7 = 0.23 \times 10^7$ cells/ml.

The rate of growth appears to be higher between days 5 and 10 compared to days 10 and 15.

(2) Overall growth trend: The *Chlorella* sp. population seems to be steadily increasing, but the rate of growth may be slowing down between days 10 and 15.

In addition to growth and density measurements, several biological assessments can provide insights into the health or stress levels of *Chlorella sorokiniana* during the treatment process like chlorophyll fluorescence, pigment composition analysis, lipid content, and composition. These assessments can offer a more comprehensive understanding of the physiological and biochemical responses of microalgae to the wastewater environment. As such, futuristic research work with these tests incorporated can be considered.

3. Results and Discussion

3.1. Test on the Checks for Water Quality. Following are the tests required for checking the quality of water for concrete mixing and curing purposes:

(1) pH value test.
(2) Limits of acidity test.
(3) Limits of alkalinity test.
(4) Chlorides.
(5) Total hardness.
(6) Total suspended solids.

3.1.1. Determination of pH. pH is a measurement scale that quantifies the concentration of hydrogen ions (H^+) within a solution. Several methods are employed to determine pH, including pH meters, which assess the electrical potential difference between a pH-sensitive electrode and a reference electrode, pH indicator papers or strips that change color depending on the pH value and pH colorimetry that employs chemical indicators undergoing color transformations at specific pH levels.

The pH scale spans from 0 to 14, where a pH of 7 is considered neutral. pH values below 7 signify acidity, with lower readings indicating greater acidity. Conversely, pH values above 7 indicate alkalinity, with higher values representing stronger alkalinity.

As indicated in Table 4, freshwater typically has a neutral to slightly acidic pH range, and a pH of 7.2 falls within this range.

STP water usually undergoes treatment processes to remove impurities and pollutants. A pH of 7.6 indicates that this water sample is slightly on the alkaline side. It is essential for the treated water to be close to neutral, but the slightly alkaline nature could be due to the treatment process or the nature of the influent.

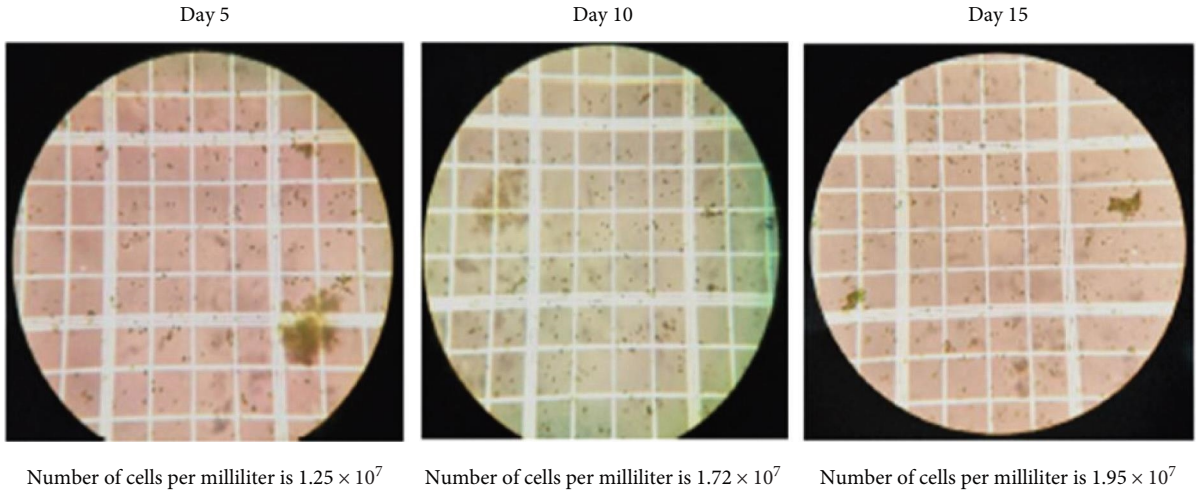

Figure 10: Haemocytometry for monitoring cell density of *Chlorella* sp.

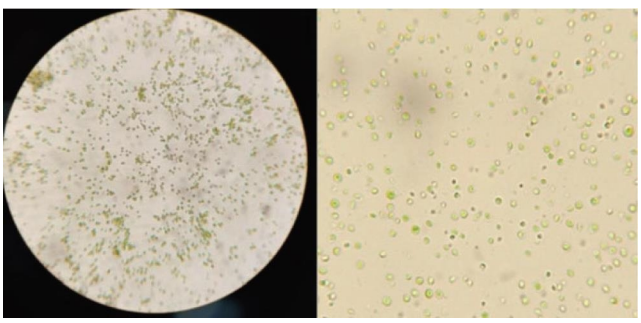

Figure 11: *Chlorella* sp. microscopic view.

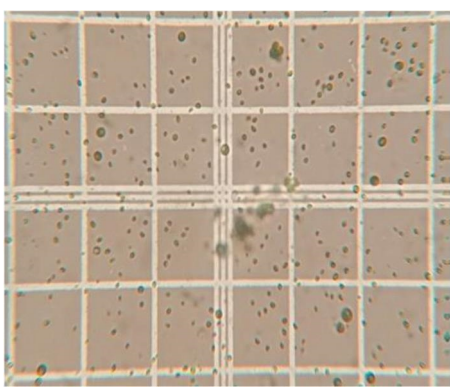

Figure 12: A magnified field of view of haemocytometer (day 15).

Algae-treated water with a pH of 8.2 is moderately alkaline. This higher pH may be attributed to the metabolic activities of algae, as they tend to raise the pH of water through photosynthesis. Monitoring the pH in algae-treated water is crucial to ensure optimal conditions for the algae and the treatment process.

The permissible value for pH is 6–8 as a tolerable concentration. So, from Table 3, the obtained results of pH value are satisfied.

Table 4: Determination of pH.

S. no.	Type of sample	pH value
1	Freshwater	7.2
2	STP water	7.6
3	Algae-treated water	8.2

Table 5: Determination of alkalinity.

S. no.	Type of sample	Alkalinity (mg/l)
1	Freshwater	138
2	STP water	180
3	Algae-treated water	248

3.1.2. Determination of Alkalinity. Determining alkalinity involves assessing a solution's capacity to resist shifts in pH toward the acidic side. Alkalinity is a measure of the concentration of carbonate, bicarbonate, and hydroxide ions within a solution, which can counteract acids and help maintain a relatively consistent pH.

Usually, alkalinity is quantified by indicating the equivalent concentration of calcium carbonate ($CaCO_3$) needed to neutralize the acidity in the solution. This measurement is typically expressed in units such as milligrams per liter (mg/l) or parts per million (ppm) of calcium carbonate.

As indicated in Table 5, freshwater with alkalinity of 138 mg/l suggests that the water has some buffering capacity to resist rapid changes in pH but is relatively low compared to other sources.

STP water with alkalinity of 180 mg/l has a higher alkalinity compared to freshwater. This higher alkalinity is often a result of the treatment process, which can involve the addition of chemicals to stabilize pH.

Algae-treated water with alkalinity of 248 mg/l indicates that the water has a strong buffering capacity against pH changes, which can be beneficial for maintaining stable conditions in algae-based treatment systems.

Table 6: Determination of acidity.

S. no.	Type of sample	Acidity (mg/l)
1	Freshwater	4
2	STP water	32
3	Algae-treated water	28

The tolerable concentration for alkalinity is less than 250 mg/l, so the obtained values are 138–248 mg/l, hence the results are satisfied.

3.1.3. Determination of Acidity. Determining acidity involves the process of assessing the concentration of acidic substances or hydrogen ions (H^+) within a solution. Various methods can be employed to determine acidity, including acid–base titration, pH measurement, and colorimetry. In acid–base titration, a standardized base solution is added to the acidic solution until the equivalence point is reached, and the volume of base solution used is then used to calculate the acidity, as shown in Table 6. pH measurement involves using a pH meter or indicator paper/strips to measure the pH of the solution, where lower pH values indicate higher acidity. Colorimetric methods utilize indicator dyes or reagents that change color when exposed to acids, allowing for visual or spectrophotometric quantification.

Freshwater typically has a low acidity level, which is indicated by the low measurement of 4 mg/l. This is considered normal for natural freshwater sources.

STP water often contains higher levels of acidity compared to natural freshwater. A measurement of 32 mg/l suggests that this water source has an elevated acidity level, likely due to the presence of organic and inorganic pollutants and chemicals in wastewater.

Algae treatment can help improve the water quality, but a measurement of 28 mg/l still indicates a relatively elevated acidity level. The acidity may be associated with residual contaminants or byproducts of the algae treatment process.

The tolerable concentration for acidity is less than 50 mg/l, so the obtained values are 4–28 mg/l, hence the results are satisfied.

3.1.4. Determination of Chlorides. Determining chloride levels entails measuring the concentration of chloride ions (Cl^-) within a solution. Typical methods for this determination include silver nitrate titration, where a standardized silver nitrate solution is introduced to the sample, resulting in the formation of a white precipitate of silver chloride, and the endpoint is determined visually. Alternatively, ion-selective electrodes designed specifically for chloride ions can be utilized to measure chloride concentration based on the generated electrical potential, as shown in Table 7. Colorimetric techniques involve using specific reagents that change color when exposed to chloride ions, with the color intensity directly correlating with the chloride concentration.

Freshwater typically contains chloride ions at relatively low concentrations. A chloride content of 94 mg/l in freshwater is within the typical range for natural freshwater sources. It suggests that this water source has not been significantly affected by contamination or human activities that would lead to elevated chloride levels.

Table 7: Determination of chlorides.

S. no.	Type of sample	Chloride content (mg/l)
1	Freshwater	94
2	STP water	94
3	Algae-treated water	78.97

Table 8: Determination of total hardness.

S. no.	Type of sample	Total hardness (mg/l of $CaCO_3$)
1	Freshwater	240
2	STP water	280
3	Algae-treated water	295

The chloride content in STP water is also measured at 94 mg/l, which is the same as the freshwater sample. This suggests that the sewage treatment process has not substantially increased the chloride levels in the water. It is important to note that chloride is a common ion in wastewater due to its presence in human waste and various cleaning products, but in this case, the levels do not appear to have increased.

Algae-treated water has a slightly lower chloride content compared to both the freshwater and STP water samples. A chloride content of 78.97 mg/l is still within the typical range for freshwater sources. The lower chloride content in the algae-treated water could be attributed to the action of algae in water treatment, which can remove certain ions and pollutants, including chloride.

The tolerable concentration for chlorides is less than 250 mg/l, so the obtained values are 78.97– 94 mg/l, hence the results are satisfied.

3.1.5. Determination of Total Hardness. Measuring total hardness involves quantifying the concentration of various dissolved cations, primarily calcium (Ca^{2+}) and magnesium (Mg^{2+}), in a water sample. Total hardness serves as an indicator of the mineral content in water, which can lead to issues like scaling and soap scum formation. Common techniques for determining total hardness encompass complexometric titration, where a chelating agent reacts with calcium and magnesium ions and colorimetric methods that utilize specific reagents to induce a color change in proportion to the hardness concentration, as shown in Table 8. The results are typically expressed in units such as milligrams per liter (mg/l) of calcium carbonate ($CaCO_3$) equivalents.

Freshwater typically contains naturally occurring minerals, including calcium and magnesium ions. In this case, the total hardness of the freshwater sample is measured at 240 mg/l of $CaCO_3$. This level of hardness is moderate and should not pose significant issues for most domestic or industrial purposes. It indicates that the water contains a reasonable but not excessive amount of calcium and magnesium ions.

STP water is typically wastewater that has undergone treatment in a STP. It may contain residual minerals from

Table 9: Determination of total suspended solids.

S. no.	Type of sample	Suspended solids concentration after filtering 11 sample (mg/l)
1	Freshwater	5
2	STP water	10
3	Algae-treated water	15

the sewage treatment process. The total hardness of 280 mg/l of $CaCO_3$ suggests that this water has a slightly higher hardness level compared to the freshwater sample. Depending on the specific application, this level of hardness may be manageable, but it is still relatively moderate.

Algae-treated water implies that some form of algae treatment or biological treatment has been applied to the water. This sample has the highest total hardness among the three, measuring 295 mg/l of $CaCO_3$. The higher total hardness may be a result of the specific treatment process or the source of water used for algae treatment. Depending on the intended use, such as for agricultural or industrial processes, the higher hardness level might require additional treatment or consideration.

The tolerable concentration for total hardness is less than 300 mg/l, so the obtained values are 240–295 mg/l, hence the results are satisfied.

3.1.6. Determination of Total Suspended Solids. The Indian code: 456-2000 specifies that if the mixing water contains suspended particles up to 0.02% by weight of the total water used in concrete, it will not have an impact on the concrete's properties. It has been observed that a high concentration of suspended particles does not influence the concrete's strength but does affect some of its other properties. The code permits the maximum limit of suspended particles in water to be less than 2,000 mg/l. Suspended particles in water are typically measured using various methods and instruments designed to quantify the concentration of solid particles that are suspended in the water column. The specific method used can depend on the size of the particles and the precision required for the measurement.

In this study, gravimetric method is used. In this method, water samples are collected and then filtered through a known-size filter membrane. The filter membrane captures the suspended particles. The filter membrane is then carefully dried and weighed before and after filtration. The increase in weight of the filter membrane after filtration provides the mass of the suspended particles in the water sample and the same is tabulated in Table 9.

The suspended solid concentration in freshwater were measured at 5 mg/l. This indicates that there are relatively low levels of suspended solids present in the freshwater sample. Low suspended solids concentrations are typical for natural freshwater sources like rivers, lakes, or wells.

The suspended solid concentration in STP water were measured at 10 mg/l. This suggests that STP water contains a moderate amount of suspended solids. It is common for treated wastewater from STPs to have higher suspended solid concentrations compared to natural freshwater sources.

The suspended solid concentration in algae-treated water were measured at 15 mg/l. This indicates that there are higher levels of suspended solids in the algae-treated water sample compared to both freshwater and STP water. The higher concentration might be a result of the specific treatment process or the presence of algae cells or other particles introduced during treatment.

In most situations, a total suspended solids concentration below 20 mg/l is found to be apt and this criterion is satisfied in this case.

3.2. Recommended Limits. The water employed for both the mixing and curing of concrete processes must meet specific criteria. It should be clean and devoid of excessive amounts of alkalies, acids, oils, salts, sugar, organic substances, vegetable growth, or any other materials that could potentially harm bricks, stone, concrete, or steel.

Potable water is typically deemed suitable for mixing. Examining up to 10% of the controlled tests is sufficient to assess the quality of the mixing water. According to IS: 456-2000, assessing the quality of mixing water can be adequately done by examining up to 10% of the controlled tests. In terms of the initial setting time, it is permissible to have a variation within ± 30 min, as long as the initial setting time is not less than 30 min. In tropical regions, particularly in lean concrete mixes, the elevated presence of chlorides in water can lead to several issues such as surface efflorescence, persistent dampness, and increased susceptibility of the reinforcement steel to corrosion. This problem associated with water quality poses a more pronounced challenge in concrete structures within tropical climates. The pH value that is most suitable for the construction of concrete is generally between 6 and 8. It is said that water equivalent to drinking water is the best for construction. The primary purpose of curing is to facilitate water penetration into the concrete. If effective measures have been taken to prevent water loss from the concrete, then curing may not require additional water. While the hydration process occurs within the interior of the structure, the situation at the surface is different, as it often lacks sufficient moisture due to evaporation. Therefore, curing becomes essential. Furthermore, if the water used for curing contains high iron content or organic matter, it can lead to staining or deposits on the concrete surface. According to IS: 456-2000, there are restrictions on the presence of iron compounds in curing water. An absolute comparison between desirable characteristics of potable water requirements and the characteristics of the freshwater, STP water and algae-treated water used is tabulated in Table 10.

The observed values for water quality parameters in freshwater, STP water, and algae -treated water were compared against the acceptable ranges defined by the IS 10500:2012 standards for drinking water. In terms of pH, all three water sources fell within the acceptable range of 6.5–8.5, with algae-treated water slightly on the higher side at 8.2. Alkalinity levels were within the permissible limit for freshwater and STP water, but algae-treated water exceeded the recommended

Table 10: Comparison between various parameters of water with reference to acceptable range for drinking water as per IS 10500:2012.

Parameter	Acceptable range for drinking water (IS 10500:2012)	Freshwater (mg/l)	Sewage treatment plant water (mg/l)	Algae-treated water (mg/l)
pH	6.5–8.5	7.2	7.6	8.2
Alkalinity	200 mg/l (as $CaCO_3$)	138	180	248
Acidity	30 mg/l (as $CaCO_3$)	4	32	28
Chlorides	250 mg/l	94	94	78.97
Total hardness	300 mg/l (as $CaCO_3$)	240	280	295
Total suspended solids	10 mg/l	5	10	15

threshold. Acidity values for freshwater and algae-treated water adhered to the standard, while STP water slightly exceeded the acceptable range. Chloride levels in all three water sources were below the specified limit of 250 mg/l, with algae-treated water showing the lowest concentration. Total hardness was within acceptable limits for freshwater but slightly elevated in STP water and algae-treated water. Total suspended solids in all cases were below the recommended threshold of 10 mg/l. These comparisons highlight the effectiveness of algae treatment in meeting certain water quality standards, while variations in alkalinity and hardness suggest the need for additional treatment or monitoring, especially in STP water and algae-treated water.

3.3. Preparation of Concrete Mix and Tests

3.3.1. Mix Design of Concrete. To design a concrete mix for M20 grade concrete (1 : 1.5 : 3), with a water–cement ratio of 0.60, following mix proportions was utilized and the subsequent tests were performed. Mix Proportions used in the study:

Cement: 300 kg/m³.
Sand: $1.5 \times 300 = 450$ kg/m³.
Coarse aggregates: $3 \times 300 = 900$ kg/m³.
Water: $0.6 \times 300 = 186$ kg/m³.

3.3.2. Slump Test. The slump test measures the workability or consistency of fresh concrete. It involves filling a standard slump cone with freshly mixed concrete, compacting it, and then lifting the cone to observe the slump (settling) of the concrete, as shown in Figure 13. The result is reported as the "slump value" and provides an indication of the concrete's ability to be placed and compacted easily.

The workability of the concrete mixes was assessed using a slump test as per the 1199-1959 guidelines. It was noted that the slump value was reduced in the concrete made with waste effluent when compared to the conventional TW mix. This decrease in workability was linked to the solid content found in the waste effluents, which exhibited a porous texture and had a significant capacity for water absorption. The test result meets the minimum requirement, which accepts a tolerance of ±50 mm and requires a minimum T_{500} flow of 2 s, as shown in Table 11 for slump flow and T_{500} values.

The concrete mix with freshwater has the highest average slump flow (708 mm), indicating good workability. The concrete mix with STP water has a slightly lower average slump flow (698 mm) compared to freshwater but is still within a reasonable range for workability. The concrete mix with algae-treated water has an average slump flow of 705 mm, which is similar to freshwater and indicates good workability. In terms of T_{500} slump flow, all three water types have relatively close values (ranging from 4.3 to 4.6 s), indicating that they have similar flow retention characteristics. Overall, based on these results, algae-treated water can be suitable replacements for freshwater in concrete mixing without significantly affecting workability or flow retention characteristics.

Figure 13: Slump test.

3.3.3. Setting Time. In the determination of the initial and final setting times of concrete, a standardized test procedure is followed using a Vicat apparatus. After preparing a concrete mix, the initial setting time is gauged by lowering a 1 mm diameter needle onto the concrete surface, recording the time, it takes to penetrate the material to a depth of 3–5 mm. Subsequently, the test continues to assess the final setting time by replacing the standard needle with a larger one (1.13 mm diameter) and recording the time it takes for the larger needle to fail to penetrate beyond 1–2 mm. The results have been tabulated in Table 12.

In the case of freshwater, the initial setting time of 30 min indicates a relatively rapid onset of the hardening process, while the final setting time of 600 min (10 hr) allows for an extended period during which the concrete gains strength. STP water, on the other hand, exhibits a slightly longer initial setting time of 48 min and a final setting time of 636 min (approximately 10.6 hr). This suggests that the impurities or treatment chemicals present in sewage water may contribute

Table 11: Determination of slump.

S. no.	Type of sample in concrete	Average slump flow (mm)	T_{500} slump flow (s)
1	Freshwater	708	4.6
2	STP water	698	4.3
3	Algae-treated water	705	4.5

Table 12: Comparison of initial and final setting times of concrete comprising of various water sources considered in the study.

Water source	Setting times (min)	
	Initial	Final
Freshwater	30	600
Sewage treatment plant water	48	636
Algae-treated water	45	630

to a delayed setting process. The setting times of concrete with algae-treated water, displaying an initial setting time of 45 min and a final setting time of 630 min (approximately 10.5 hr), exhibit characteristics that can be rationalized as falling between those observed with freshwater and STP water. The initial setting time, at 45 min, is longer than that of freshwater (30 min) but shorter than STP water (48 min). This suggests that the presence of algae or the treatment process applied to the water may slightly extend the onset of the hardening process compared to freshwater but is faster than that observed with sewage water. The final setting time of 630 min aligns more closely with the setting time of freshwater (600 min) but is notably shorter than that of STP water (636 min). This indicates that while algae-treated water allows for a prolonged period for concrete to gain strength similar to freshwater, it still exhibits a shorter overall setting time compared to STP water.

Further, the presence of ammonia in algae can interfere with the setting time of concrete, affecting the workability and the early strength development. High concentrations of phosphates can act as retarders, slowing down the setting time of concrete.

3.3.4. Compressive Strength of Concrete. M20 concrete samples are prepared by using freshwater, STP water, and algae-treated water separately considering the strength considering the average of three samples. Concrete's compressive strength denotes its capacity to withstand compression and endure a load without experiencing deformation or failure. This property holds significant importance in construction applications as it governs the cement's structural stability and its ability to bear loads. The standard method for assessing compressive strength involves subjecting cement samples to progressively increasing compressive forces until they reach the point of fracture. Twenty-seven concrete cubes of size 150 mm × 150 mm × 150 mm were cast (Figure 14) and tested in the compression testing machine (Figure 15). The highest force at which the specimen fails (Figure 16) is measured for 7, 14, and 28 days postcuring and the same is tabulated in Table 13 along with a comparison graph (Figure 17).

Figure 14: Cube casting.

Figure 15: Compression testing.

In the case of freshwater, the compressive strength of concrete typically increases with time due to the continued hydration and development of the cementitious material. We see a noticeable increase in compressive strength from 7 days (13 MPa) to 14 days (18 MPa) and further to 28 days (19.8 MPa). This increase is expected and indicates that the concrete mixed with freshwater is gaining strength as it cures over time.

In the case of STP water, the compressive strength of concrete increases with curing time. However, the compressive strength values for STP water are consistently lower than those for freshwater at all three curing times. This could be due to impurities or constituents present in the STP water that may affect the cement hydration process or the development of strength.

Figure 16: Crack developed posttest in algae-treated water incorporated specimen.

Table 13: Compressive strength of concrete produced using freshwater, STP water, and algae-treated water after 7, 14, and 28 days of curing.

S. no.	Type of sample	Compressive strength value (MPa)		
		7 days	14 days	28 days
1	Freshwater	13	18	19.8
2	STP water	10	13.8	16.7
3	Algae-treated water	12	17.6	19

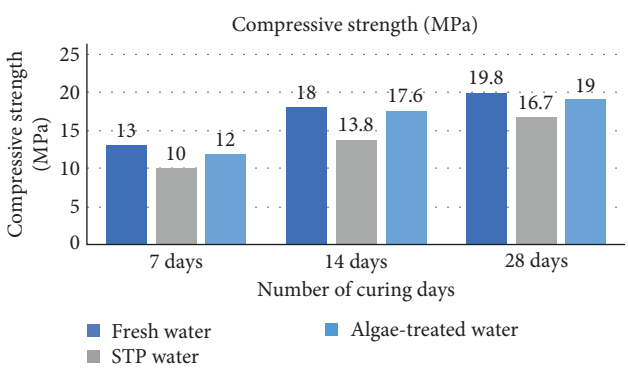

Figure 17: Graph depicting 7-, 14-, and 28-days compressive strength for samples produced from freshwater, STP water, and algae-treated water.

Furthermore, in algae-treated water, similar to the other two samples, the compressive strength of concrete with algae-treated water increases with curing time. The compressive strength values for algae-treated water are between those of freshwater and STP water at all curing times. The presence of algae-treated water may introduce certain organic or biological factors that could impact the hydration process, but overall, the concrete is still gaining strength over time.

3.3.5. Split Tensile Strength Test. To determine the split tensile strength of concrete following IS: 5816-1999, 27 cylindrical specimens are cast and cured. The ends are prepared, and specimens are tested horizontally using a universal testing machine with spherical seating. Load was applied until failure, recording maximum load (P_{max}) and failure load (P_f). Split tensile strength (f_{ct}) was then calculated as $\frac{2P_f}{\pi DL}$. A minimum of three tests were conducted, and the average result is reported in Table 14 and Figure 18. The test specimen is shown in Figure 19.

Table 14: Split tensile strength of concrete produced using freshwater, STP water, and algae-treated water after 7, 14, and 28 days of curing.

S. no.	Type of sample	Split tensile strength (MPa)		
		7 days	14 days	28 days
1	Freshwater	1.14	1.34	1.41
2	STP water	1	1.17	1.29
3	Algae-treated water	1.1	1.33	1.38

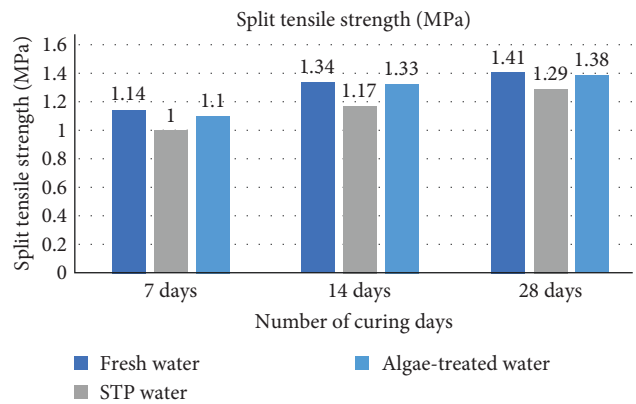

Figure 18: . Graph depicting 7-, 14-, and 28-days split tensile strength for samples produced from freshwater, STP water, and algae-treated water.

Figure 19: Split tensile strength test specimen for STP water added samples.

The split tensile strength values for concrete samples mixed with freshwater, STP water, and algae-treated water exhibit consistent trends over different curing durations. In freshwater, the strength gradually increases from 7 days (1.14 MPa) to 14 days (1.34 MPa) and 28 days (1.41 MPa), showcasing the ongoing development of tensile strength during the curing process. For concrete mixed with STP water, the split tensile strength follows a similar pattern, starting at

1 MPa at 7 days and increasing to 1.17 MPa at 14 days and 1.29 MPa at 28 days. These values, though slightly lower than those with freshwater, indicate comparable tensile strength development. In the case of concrete mixed with algae-treated water, the split tensile strength values at 7 days (1.1 MPa), 14 days (1.33 MPa), and 28 days (1.38 MPa) align closely with those of freshwater and STP water. The presence of algae treatment appears to have minimal impact on the overall tensile strength development. Overall, these results suggest that, in this study, both STP water and algae-treated water, when used as mixing water, maintain concrete tensile strength comparable to that achieved with freshwater. The observed variations are minor, indicating that alternative water sources do not significantly affect the tensile strength development of the concrete during different mixing periods.

The addition of algae-treated wastewater to concrete mixes can have several effects on the compressive strength of the resulting concrete. However, there are certain factors associated with the use of treated wastewater that may contribute to a decrease in compressive strength.

High pH levels: Algae-treated wastewater have elevated pH levels after it has undergone a treatment process. High pH can adversely affect the hydration process of cement, leading to the formation of weak and porous structures in the concrete thus resulting in reduced compressive strength.

Chemical composition: The chemical composition of treated wastewater, including residual chemicals from the treatment process, may not be entirely compatible with the cement matrix. Algae can assimilate nitrogen compounds, including ammonia (NH_3) and nitrate (NO_3^-), as part of their growth process. Ammonia can increase the alkalinity of the concrete pore solution. Elevated alkalinity can potentially accelerate the corrosion of certain metals, such as aluminum or zinc, if they are embedded in the concrete. However, the effect on the overall concrete structure is generally limited. Nitrate is often associated with the nitrogen cycle and the potential for biological activity. Microbial action in the presence of nitrates can lead to the production of nitrites and ammonia, which may impact concrete in multiple ways. High alkalinity resulting from ammonia or other sources can potentially contribute to alkali-aggregate reaction (AAR), especially if reactive aggregates are present in the concrete mix. AAR can lead to the formation of expansive products which might cause cracking and reducing the concrete's durability.

Algae can also absorb phosphorus from wastewater, typically in the form of phosphate (PO^{3-}). Excessive amounts of phosphates in concrete can potentially lead to a reduction in compressive strength. This effect is more significant in concentrations higher than what is typically found in natural water sources. The impact on strength is related to the interaction between phosphates and the cement hydration process. Some chemicals in the treated water may react with the cement, affecting the strength development and overall performance of the concrete.

Influence on cement hydration: Treated wastewater may contain substances that can affect the hydration process of cement. Algae residues or by-products in the water might act as pozzolanic materials, potentially slowing down or altering the cement hydration reactions and negatively impacting strength development.

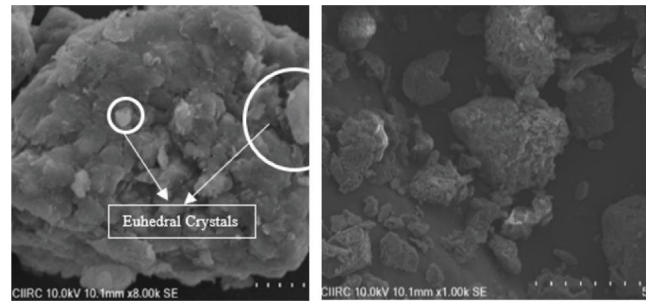

Figure 20: Presence of euhedral crystals in the sample produced using algae-treated wastewater.

Increased porosity: The use of treated wastewater may introduce additional porosity into the concrete matrix. Increased porosity can weaken the concrete structure and reduce its ability to resist compressive forces.

Effects of organic matter can be in algae residues and effect the quality of treatment process.

Algae residues: Residual organic matter or algae remnants in the treated wastewater may introduce additional organic compounds into the concrete mix. These compounds can interfere with the hydration reactions, reducing the strength of the concrete.

Quality of treatment process: The effectiveness of the wastewater treatment process can vary. If the treatment process is not thorough or if certain contaminants are not adequately removed, the treated water may still contain substances that can compromise the concrete's strength.

3.3.6. Microstructural Analysis. The scanning electron microscope (SEM) images of concrete samples produced using algae-treated wastewater provide valuable insights into the microstructure and crystalline characteristics of the material. In Figure 20, the presence of euhedral crystals is observed, indicating that the crystals have well-defined and sharp edges. However, the gaps or voids between these crystals are more pronounced when compared to concrete made using freshwater. The increased voids or gaps in the concrete produced with algae-treated wastewater can be attributed to several factors. Algae-treated wastewater may contain organic compounds or nutrients that influence the hydration process of the cement, potentially leading to the formation of crystals with distinct characteristics. The interaction between these compounds and the cementitious materials may result in the development of crystals with less cohesion, allowing for more evident voids or gaps in the microstructure.

On the other hand, SEM images of the concrete samples prepared using freshwater, as shown in Figure 21, reveal the formation of subhedral to anhedral crystals. Subhedral crystals have partly defined edges, while anhedral crystals lack well-defined shapes. This suggests that the crystals in the freshwater concrete are more compact and exhibit a denser structure compared to those in the algae-treated wastewater concrete. The reduced voids in the freshwater concrete

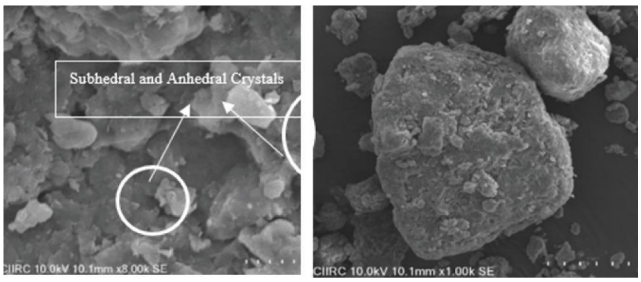

Figure 21: Presence of subhedral and anhedral crystals in prepared using freshwater.

contribute to its overall denser appearance. The observed differences in crystal formation and void content between the two concrete types support the notion that the use of algae-treated wastewater as a mixing water source can influence the microstructure of the concrete. The organic constituents or nutrients present in algae-treated wastewater may impact the hydration kinetics and crystal growth, leading to a microstructure with more pronounced voids.

4. Conclusion

The following are some of the conclusions that may be derived from the results of the study:

(1) With phycoremediation technology, one can easily tackle more than one problem like sludge removal, pH correction, TDS reduction, BOD and COD removal, etc., with the least ecological and environmental impacts, which is difficult to achieve with the currently used treatment processes as they need separate treatment methods at every treatment stage and hence this novel process can be employed in the existing wastewater treatment plants with suitable modifications and the process can be cheaper and easier to adopt as it can lower the cost of wastewater treatment by up to 90%. Microalgae's absorbance at 660 nm demonstrated a consistent increase over time, indicating rising cell concentration. This positive correlation suggests healthy, exponential cell growth, particularly between days 9 and 15. Over the 15-day period, *Chlorella* sp. displays continuous growth in cell density.

(2) The rate of growth is more pronounced between days 5 and 10, suggesting a potential slowdown in growth between days 10 and 15. The specific compressive strength values differ between the water samples, with freshwater producing the highest strength, followed by algae-treated water and STP water. These differences may be attributed to the composition and quality of the water sources, including the presence of impurities or substances that can influence the hydration of cementitious materials. In light of the findings, it appears that water treated with algae can serve as a viable substitute for freshwater in concrete mixing, with minimal impact on both workability and the ability to retain flow characteristics. Concrete mixed with STP water and algae-treated water demonstrated comparable split tensile strength to that of freshwater across varying curing durations. The minor variations observed imply that STP and algae-treated water are viable alternatives for concrete mixing, exhibiting consistent tensile strength development.

(3) SEM images of concrete from algae-treated wastewater reveal euhedral crystals with noticeable voids, while freshwater-produced concrete displays subhedral to anhedral crystals with denser structure and fewer voids, indicating differences in crystal formation and density.

In conclusion, the exploration of green microalgae-based phycoremediation treated wastewater for sustainable concrete production presents a promising avenue for environmentally conscious practices in the construction industry. The integration of phycoremediation-treated wastewater as a water source in concrete production not only contributes to wastewater management but also aligns with sustainable development goals. This study sheds light on the practical significance of utilizing microalgae-treated wastewater in concrete mixes, offering potential benefits for both the construction industry and environmental conservation.

The practical significance includes a sustainable approach to water management, addressing the growing concerns related to freshwater scarcity along with resource efficiency by repurposing a waste stream as a valuable resource. This practice aligns with circular economy principles, promoting responsible consumption and production in the construction sector. Further, environmental impact mitigation involves the potential of reducing the environmental impact associated with traditional wastewater disposal methods. Practitioners can contribute to environmental conservation by adopting phycoremediation as a means of wastewater treatment for sustainable concrete production.

(1) Economic viability: The practical significance extends to potential economic benefits, as the use of treated wastewater may lead to cost savings in water acquisition for concrete mixing. This information is valuable for practitioners seeking both environmentally friendly and economically viable solutions.

(2) Regulatory compliance: The study underscores the importance of ensuring compliance with water quality regulations when using microalgae-treated wastewater. Practitioners should stay informed about local regulations and work collaboratively with regulatory bodies to meet environmental standards.

(3) Research and development opportunities: The findings open avenues for further research and development in the field of sustainable construction materials. Practitioners are encouraged to explore innovative approaches and collaborate with researchers to advance the practical applications of microalgae-based phycoremediation in concrete production.

By incorporating these insights into construction practices, practitioners can contribute to a more sustainable and

resilient built environment. The responsible use of microalgae-treated wastewater in concrete production aligns with global sustainability goals, providing a tangible way for the construction industry to reduce its environmental footprint while fostering economic viability. Continued collaboration, education, and implementation of such sustainable practices will be crucial for the advancement of green initiatives in the construction sector.

The integration of algae-based treatment processes into existing wastewater treatment facilities involves a comprehensive approach to enhance the overall efficiency and sustainability of the treatment system. Initial feasibility studies are conducted to assess the compatibility of algae-based treatment with the specific characteristics of the wastewater. Pilot-scale testing can then be employed to evaluate the process's performance, addressing challenges, and determining scalability. Selection of suitable algae strains, optimization of growth conditions, and efficient harvesting and separation methods are critical components of the integration process. The algae-based treatment system is strategically incorporated into existing processes, targeting nutrient removal through algae's natural uptake mechanisms. Monitoring and control systems ensure the reliability and compliance of the integrated system with regulatory standards. Scalability considerations, economic viability, and public outreach are carefully addressed, taking into account factors such as land availability, water resources, and stakeholder concerns. The long-term success of the integration relies on ongoing maintenance, continuous optimization, and collaboration between experts in biology, engineering, and environmental science, fostering a sustainable and effective solution for wastewater treatment.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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