SOLAR ENERGY BASED HYBRID SYSTEM FOR THE TREATMENT OF DYE INDUSTRY WASTEWATER

SUMMARY
of
THESIS

SUBMITTED TO
BABASAHEB BHIMRAO AMBEDKAR UNIVERSITY

BABASAHEB
BHIMRAO
AMBEDKAR
UNIVERSITY
LUCKNOW
प्रज्ञा शील करुणा
ESTABLISHED 1996

FOR THE DEGREE OF

Doctor of Philosophy
IN
ENVIRONMENTAL SCIENCE

Submitted by

Pradeep Kumar Majhi

Enrollment No: 1277/15

Under the Supervision of

Co-supervisor
Dr. Richa Kothari
Associate Professor
Department of Environmental Science
Central University of Jammu
Samba
Jammu & Kashmir-181143

Supervisor
Dr. Naveen Kumar Arora
Professor
Department of Environmental Science
School for Environmental Sciences
Babasaheb Bhimrao Ambedkar University
(A Central University)
Lucknow-226025

2022

1. Introduction

According to the current systematic statistical scenario of pollution, the earth is in grave danger from itself and environmental pollution is generally cited as one of the most serious threats facing humanity. These serious environmental problems are the results of *Homo sapiens'* unconscious anthropogenic actions, such as industrialization, urbanization, deforestation, and population growth, which result in serious environmental problems such as greenhouse gas emissions, energy shortages, and water contamination. Water contamination is the most serious of all the pollutions because of its uncontrolled, insensitive use, particularly in the industrial and urban growth sectors. Water, on the other hand, is widely used by societies and humans, yet it is frequently mistreated in terms of environmental pollution. Only 1% of the world's freshwater is available for human consumption willingly.

Colors are still prevalent in human sentiments because they are a part of human culture and lifestyle. These are common dyes that have been used to create a variety of textile items in a variety of industries. When toxic dyes come into contact with surface water, aquatic species face a serious threat to their survival. These dyes are chemical substances that attach to surfaces or fabrics and color them. Due to its tenacity, dye ejection into the hydrosphere is a major source of pollution. It dries out water, inhibits sunlight penetration, and prevents aquatic flora and fauna from photochemical and biological activity. According to estimates, there are over 100,000 commercial dyes, with an annual production of over 7×10^5 tonnes. Total dye consumption in the textile industry exceeds 10,000 tonnes per year, with approximately 100 tonnes of dyes discharged into waterways each year. The vast majority of dye-contaminated textile manufacturing industries are concentrated in Asia. Dye-contaminated textile industries consume more quantity of dyestuffs (about 80% of the total dye production). India has become a major exporter of dyestuffs and dye intermediates, particularly reactive, acid, vat, and direct dyes. Textile and dye processing, both of which use a wide range of dyes and chemical additives, are two of the most important industries that generate dye wastewater. The dyeing and finishing operations, which involve the input of a diverse range of chemicals and dyestuffs, the majority of which are organic compounds with complex structures, are the main units in these dye-using industries. The removal of color from textile and dyestuff manufacturing industry wastewaters is a serious environmental concern.

1.1 Textile production

Textile manufacturing is one of the world's largest and oldest industries. Textile production has shifted to countries with lower labor and material costs in Asia, particularly China, India, and Bangladesh, supply more than half of the clothing and textiles consumed in the United States and the European Union. The textile industry has grown to be one of the most important business sectors in the majority of these countries, and significant efforts are being made to boost production. The textile industry consumes a lot of water and has spread to nearly every part of India. It comes in composite and semi-composite forms. Uttar Pradesh, Andhra Pradesh, and West Bengal have 80, 54, and 40 textile industries respectively. Because of its toxicity and chemical nature, environmental scientists face significant challenges in the remediation of textile industry wastewater. In general, wastewater from the textile industry can be treated using both conventional and advanced treatment methods. Traditional treatment methods include all common handling technologies such as physical, chemical, and biological treatment options, whereas advanced treatment methods include the highly developed function of contemporary techniques such as the use of nanomaterials, ion exchange treatment, reverse-osmosis, biomass-based treatment, and solar-energy-based treatment.

1.3 Hybrid treatment option

Because of specific limitations in individual treatment methods, a single treatment method for pollution reduction of textile dye effluent is not fully capable of reducing pollutants. As a result, the idea of combining more than one treatment system could be the best solution in this context, resulting in the advent of hybrid treatment technology. In this scenario, merging more than one treatment system may be the best solution, as merging more than one treatment system not only improves treatment efficiency but also reduces the formation of secondary pollutants. In this regard, for the current study, solar energy and algal biomass-based treatment have been hypothetically constructed and integrated for improved results in the treatment process quality.

The thesis has been divided into the following six chapters:

Chapter 1: Introduction and review of literature

Chapter 2: Materials and Methods

Chapter 3: Phycoremediation of textile industry wastewater by *C. pyrenoidosa*

Chapter4: Experimental evaluation of solar energy-based setup for the treatment of dye contaminated textile industry wastewater

Chapter 5: Experimental evaluation of novel Solar-Algal Hybrid Reactor for dye contaminated textile industry wastewater treatment: techno-economic assessment

Chapter 6: Conclusion and future recommendations

The chapter-wise description of the work is as under:

Chapter 1: Introduction and review of literature

This chapter provides an overview of dye-contaminated textile industry wastewater availability, sources of generation, and environmental impacts. The numerous treatment technologies for dye-contaminated textile industry wastewater have been described, together with their benefits and drawbacks in terms of the environment. This study's literature review covers various treatment alternatives such as physical, chemical, biological, and highly sophisticated treatment technologies for the treatment of dye contaminated textile industry wastewater. After that, several objectives have been decided based on the literature survey to be fulfilled by the current study.

Chapter 2: Materials and Methods

This chapter elaborates the experimental methodologies those were used for this investigation. Each experiment's goal and analytical technique have been thoroughly addressed. It describes textile industry wastewater, its properties, the primary wastewater parameters involved, its reactive nature toward the adsorbent, *C. pyrenoidosa* algae as an adsorbent, its adsorptive behavior toward pollutants, and dye removal from textile industry wastewater. This chapter also derivates scope on industrial thoughts on the immobilization process, its impacts on the industrial sector in terms of pollution reduction in various wastewater. This chapter describes the mechanism for the preparation of immobilized algae. In this study, solar energy is an important aspect of pollution reduction and has been discussed how to build up a solar energy-based treatment system to reduce pollution. The algal-based setup, solar-energy-based setup, and hybrid-based setup all have been summarized here. All of the materials and methodologies utilized for this study have been explained in the sections that follow:

Experimental design

As per the objectives, the present research work has been divided into three phases (Phase-I, II, and III) to make it more fruitful with significant findings such as:

- **Phase-I:** Algal based treatment
- **Phase-II:** Solar energy-based treatment
- **Phase-III:** Hybrid treatment (combination of both solar and algal-based treatment technology)

Experimental plan used for current research work

Phase-I (Chapter-3)	Phase-II (Chapter-4)	Phase-III (Chapter-5 and 6)
Phase-I Phycoremediation of dye contaminated textile industry wastewater by using both free and immobilized *C. Pyrenoidosa*	**Use of Solar Parabolic Trough Reactor (SPTR) for treatment of dye contaminated textile industry wastewater**	**Use of hybrid treatment setup for textile industry wastewater and comparative assessment among algal, solar and hybrid treatment system**
Selection of sampling site, collection of samples, and its initial physico-chemical characterization. Algal growth with BG-11 media. Phycoremediation of dye industry wastewater using microalgae *C. pyrenoidosa* by Free Algal Cell (FAC) and Immobilized Algal Cell (IAC) • Dose, pH, and temperature optimization with the best result obtained between FAC and IAC • Data assessments-Study, Statistical analysis, SEM, DES study of *C. pyrenoidosa*. The optimized results are to be used for hybrid treatment setup.	Solar energy based setup to be designed in lab-scale and textile wastewater was treated with it The process parameters (flow rate) to be optimized and the best result to be considered for the hybrid treatment system.	The hybrid setup was designed in lab-scale Textile wastewater to be treated with designed hybrid setup with optimized experimental condition (dose, pH, and flow rate) • Impact of flocculants, dose, pH, flow rate on pollution and color reduction efficiency Cost-effectiveness and eco-friendly assessment

Chapter 3: Phycoremediation of dye contaminated textile industry wastewater by *C. pyrenoidosa*

The chapter discusses how *C. pyrenoidosa* has been used to minimize pollution and color in dye contaminated textile industry wastewater. The major objective of this experiment was to grow *C. pyrenoidosa* algal strain textile industry wastewater and investigate its potential for pollution reduction and color removal from textile industry wastewater**.** The algal strain grows in the textile industry wastewater by utilizing the nutrients like nitrate and phosphate available in the wastewater. When the nutrient availability is more the growth rate of algal strain is more. Again the growth depends on external factors like pH, light, and temperature of the surroundings. All these multiple variables are responsible for the growth as well as treatment of textile industry wastewater. Here, for the present study, the real textile industry wastewater was taken rather than synthetic wastewater, to make the process practically applicable. To study the potential of *C. pyrenoidosa* cell with real type textile industry wastewater for dye removal and pollution reduction experimentally, it was investigated with two concentrations of test solution (50% & 100%). The best pollution reduction efficiency between the two concentrations (50% and 100%) was calculated by analyzing the wastewater parameter of textile industry water before and after the growth period. The textile wastewater concentration (between 50% and 100%) where the best result for color removal and pollution reduction was only retained rather than the other one during this present experiment. Then another experiment was conducted for the pollution reduction and color removal of textile industry wastewater with immobilized algal biomass. The process of immobilization is a highly modern scientific procedure being applied in recent industrial as well as research areas. The mechanism of immobilization of *C. Pyrenoidosa* has been discussed in the following section:

3.1 Immobilization of algal cells: process & mechanism

Algal cells were immobilized with sodium alginate in a batch procedure using aqueous solution of alginate. In the laboratory, 1.5% sodium alginate solution and 2% $CaCl_2$ solution were prepared and the sodium alginate solution was then merged with the healthy algal cell suspension in a 1:1 ratio. A homogeneous mixture (natural polymer derivative of algal polysaccharide) was achieved by gently combining the algae and alginate. To achieve a homogeneous and circular surface, the algae-alginate mixture was added to a 2% $CaCl_2$ solution using a syringe pump (TRUTH glass surgical size: 20 mL, Luer-Lok tip with 30 mm needle size). When the mixture comes into contact with the $CaCl_2$ solution, the alginate entraps the algal beads and hardens them into homogeneous circular algal beads. Water may pass through alginate and into the bead because it is a hydrophilic polymer and before being utilized as a dye adsorbent, these algal beads were cleaned and maintained in distilled water.

The current study was split into two phases: the impact of (a) free algal cells (FAC) and (b) immobilized algal cells (IAC) on wastewater. On the basis of comparing results, the best cells were explored further at various temperatures. The real wastewater has been used for this study rather than artificial/ synthetic wastewater, as it has been researched in small numbers by researchers. Only two specific concentrations were chosen to identify the exact adsorption rate under real-world wastewater conditions. Pollution reduction with free algal biomass showed its efficient nature towards reduction of high loaded nutrients as well as major wastewater parameters. It was observed that nutrients like nitrate and phosphate were reduced by 43.2% and 56.7% respectively and COD was reduced by 78.0% and similarly, BOD was reduced by 71.4%, at the same time TSS and TDS were reduced by 15% and 36% respectively and 76% of chloride was also reduced by using free algal cell. Again, the free algal biomass was converted into immobilized algal form by using the standard scientific protocol. Here, the same quantity of the algal biomass was used for the preparation of immobilized algae so that, the difference between free and immobilized algal biomass could be justified and it was concluded that the immobilized algal biomass used for pollution reduction was drastically capable to remove undesired substances like organic pollutants, metals, and nutrients, *etc*. It was observed that where 56.7% of phosphate was reduced with free algal biomass, 59.4% of phosphate was reduced by immobilized algal biomass. Similarly, 43.2% of nitrate, 71.4% of BOD, 78.0% COD and 46.7% nitrate, 73.3% BOD, and 83.0% of COD were reduced with free algal biomass and immobilized algal biomass respectively. The experimental data also revealed that using the free algal cell as an adsorbent resulted in a considerable decolorization efficiency from dye contaminated textile industry wastewater, with 74% removal efficiency from a 50% test solution and 67.6% removal efficiency from 100 % test solution and the specific uptakes of contaminants from dye industry wastewater were determined to be 1.04 and 1.94 using 50% and 100% test solutions, respectively. The dye removal effectiveness rapidly decreases as the concentration of test solutions increases. As a result, 87% of the dye was removed from the 50% test solution, but only 77% of the dye was removed from the 100% test solution. The specific uptakes of pollutants from dye industry wastewaters are 1.23 and 2.22 in 50% and 100% test solutions, respectively.

The highest decolorization removal was obtained with IAC (87%) in a 50% test solution, while the lowest removal was obtained with FAC (67%) in 100% test solution, according to the above comparative study between IAC and FAC as an adsorbate. The surface area between FAC and IAC is the major adsorption process and factor that causes the variation in removal efficiency. The greater surface area offers more contact space between dye molecules and algal cells, allowing dye molecules to bind to the immobilized algal cells more easily. Cell wall characteristics of algal biomass, according to Satiroglu et al (2002), play an essential role in biosorption, which is regulated by electrostatic attraction. The experiment revealed that the rate of decolorization was excessively high in the beginning compared to the later phase. However, because it is dependent on the availability of dye molecules or the volume of the adsorbate, adsorbent, and the potential charge difference, it becomes slower with time. Hameed et al (2007) and Karagoz et al (2008) found similar results, and that is that the adsorption rate is higher at the beginning than in later phases. Furthermore, because alginate is an extracellular polymer with surface functional groups, it helps in the sorption of dye molecules onto the surface of the polymer during the dye removal process. This might be due to the release of metabolic intermediates with high coagulation capacity, as well as the dye remaining in the wastewater preferring to adsorb and settle on the surface of the polymers. A specific experiment was performed using four different temperature ranges (30°C, 40°C, 50°C, and 60°C) using 50% test solution to analyze the effect of temperature on decolorization efficiency. The dye removal rate was 92% at 30 °C, and 94 % at 40 °C, according to the current study. At 50°C, the dye removal efficiency was highest (98%); however, when the temperature rises (60°C), the dye removal efficiency drops from 98 to 97.5 %.

Chapter 4: Experimental evaluation of solar energy-based setup for the treatment of dye contaminated textile industry wastewater

The Solar Algal Trough Reactor (SPTR) was fabricated for the treatment of dye contaminated textile industry wastewater. This setup has been based on the CPS principle. Here, this parabolic solar collector has been designed in movable way that it can manually track the sun from east to west during the treatment process. The parabolic reflecting surface concentrates the direct solar radiation on the receiver tube creates heat and enhancing the wastewater treatments process. The SPTR has six important parts such as: reflecting aluminum surface, transparent glass tube, wastewater tank. The parabolic reflective surface is made up of 1.5 mm of aluminum metal with the length of 2 meters and the glass tubes are 2 meters in length with 1.5 mm thickness. Over the aluminum surface, these three connecting glass tubes have been connected in a parallel form, and connectors of hard plastic joint them so that wastewater can easily flow over the reflector. The wastewater tank is of 10 liter capacity with the working volume of 8 liters. To flow water through the designed reactor an electric motor of 0.5 hrz power has been used. The whole designed setup stands over a woody stand which is designed in such a way that can track solar radiations manually in the daytime. The solar intensity was measured by solar intensity measurement device (KM-SPM-530) in W/m^2 for a total of 15 days with one-hour intervals on each day. Treated wastewater was collected and analyzed for physico-chemical parameters on each 5^{th} day of the experimental duration. The initial characterization of wastewater and final characterization of wastewater were performed to conclude the potential of SPTR for the reduction of pollutants from textile industry wastewater.

According to literature, when the BOD and COD ratio (B/C ratio) is 0.5, wastewater is quickly biodegradable, when it is 0.4-0.6, it is average biodegradable, when it is 0.2-0.4, it is steadily biodegradable, and when it is less than 0.2, it is non-biodegradable. The B/C radio of the collected wastewater sample was detected at 0.5, which is most appropriate for wastewater degradation. The experiment was performed using a solar-powered built reactor based on more degradability hypothesis. With varying circulation rates, substantial color and COD reduction were observed. The highest COD reduction (10%) and decolorization (13%) were obtained at 1.95 L/M, while the lowest COD reduction (7%) was obtained at 0.65 L/M. COD was reduced 8.8% and 9.2% with 1.3 L/M and 2.6 L/M respectively. As a result, the flow rate of 1.95 L/M was considered the most efficient flow rate for the present experiment. The flow rate allows the wastewater molecules to move over the reflecting surface, increasing the randomness of the wastewater molecules and reducing the color concentration. However, after a certain flow rate, the contact time decreases, whether the flow rate is very high or very low. Color removal from dye-contaminated textile industry wastewater was seen significantly higher by this solar energy-based treatment reactor and it was observed ≥76% of color concentration was reduced from the initial concentration. The high-intensity ultraviolet solar radiation is capable of breaking down the toxic chemical bonding and, at the same time, could be highly efficient for color removal from the dye-contaminated textile industry. The pollutant load of COD was reduced by 79% from the dye effluents, but other pollutional parameters like BOD, nitrate, and phosphate were reduced very less as compared to COD. The color concentration was reduced by 76.4% after the treatment by the solar parabolic trough reactor.

Chapter 5: Experimental evaluation of novel Solar-Algal Hybrid Reactor for cost-effective wastewater treatment: techno-economic assessment

The Solar algal Hybrid Reactor (SAHR) is an innovative and renewable-based low-cost setup where immobilized *C. pyrenoidosa* was used as an adsorbent in coupling with concentrating solar energy-based treatment. The literature and review concluded that a single treatment is insufficient to treat the textile industry wastewater with very high efficiency as major gaps have remained in a single treatment system. To fulfill these gaps SAHR was fabricated. This is a model where two treatment setups are connected adjacent to each other and the solar energy-based treatment and algal-based treatment are connected with a single reactor. The algal chamber was 8 L capacity with working volume of 6 L. This immobilized algal chamber was attached in such a way that the textile wastewater will flow through the glass tubes (three) which are fixed over the parabolic trough and the same wastewater will flow through the immobilized algal chamber. The SAHR potential is dependent on the process parameters like pH, flow rate, and contact, and temperature. Throughout the experiments, the solar radiations were seen to have fluctuated randomly. However, in order to assess its influence on pollution reduction, the wastewater parameters were examined at regular intervals. Initially, pollutant reductions like COD and BOD were reported to be 68%and 63%, respectively (approximately in the first five days). Similarly, nitrate and phosphate levels were reduced by 56% and 42%, respectively. Gradually, pollutant reduction becomes slower; this could be due to immobilized algal dosages reaching saturation or threshold limitations on a daily basis. It was noticed that COD reduction was obtained by 90% whereas the COD reduction was obtained only 83% by algal-based treatment and 79% by solar energy-based treatment. This indicates the efficiency of the hybrid treatment than both treatment systems. It was also noticed that the other pollutional parameters like BOD, nitrate, and phosphate were also reduced more efficiently as compared to both the single treatment ones. About 77%, 70%, and 60% of BOD, nitrate, and phosphate were reduced respectively by SAHR whereas in algal and SPTR the reduction potentially lowers for pollutant as well as nutrient load. Moreover, it was also found perceptible color reduction from wastewater by hybrid setup. The maximum color reduction was obtained by solar hybrid setup than single treatment system like solar and algal-based treatment. The other physicochemical parameters also showed similar observations. TDS and TSS were reduced by 49% and 47% respectively. It was observed that most of the parameters have been efficiently degraded in hybrid treatment than individual treatment. It is because of the integration technology between algal and solar energy-based treatment.

5.1 Comparative discussion of solar, algal, and hybrid treatment for dye contaminated textile industry wastewater

It is well known that conventional treatment technologies have the potential for the treatment of any wastewater which could be tannery, dairy, or textile industry wastewater. But, some sort of disadvantages like secondary pollutant generation, treatment efficiency, and cost-effectiveness make them less preferable. Here, two separate treatment options have been utilized for the dye contaminated textile industry wastewater treatment at the same time both the treatment technologies have been coupled to check where they are best capable for pollution minimization and the conclusion is very interesting and valid. The effect of conventional algal-based treatment was observed quite proficient on pollution as well as color removal. In the same way, the implication of solar parabolic through reaction over the toxic dye contaminated textile industry wastewater should the same result. Though it can be hypothesized that the algae-based treatment is typical process of adsorptive, so that the reduction of all the pollutional parameters like nitrate, phosphate, and BOD are higher due to more pathogenic activities. But in SPTR due to the strong radiance effect of ultraviolet radiation keeps minimizing the impact of pathogens on the text solution therefore, reduction of all the pollutional parameters is very less in comparison to algal-based treatment. But, the color concentration was reduced by each treatment technology and at the same time, the COD values were also reduced at a significant value. It was seen the reduction values of color concentration by designed hybrid setup was more as compared to both the separate treatment technology. The estimated value of color reduction by solar energy-based treatment was 76%, similarly <=98% by algal-based treatment but it >98% when we merge both the treatment system means by the hybrid treatment system. The main mechanism of pollution reduction by hybrid treatment is due to both adsorption and solar radiation. The *C. pyrenoidosa* has been used for the same purpose where it will process the adsorption process of the highly toxic compounds, which have been broken down by high-intensity solar radiation. The high-intensity solar radiation is capable to break the toxic chemical bonds of non-biodegradable dye wastewater flowed by algal-based chamber which is the best fit and capable for the pollution and nutrient load reduction from wastewater. Due to differences in the pathogenic activities, the reduction values of pollutional parameters differ in each treatment technology. In solar energy-based treatment, the pathogenic activities are very less so the pollutional parameters like nitrate, phosphate, and BOD are degraded in very less amounts. But the COD reduction efficiently occurred in all three treatment technologies adopted for experimental investigation.

5.2 Cost-effectivness

The conventional handling technologies necessitate supplementary energy input for treatment progression, at the same time these techniques discharge enormous quantity of the poisonous substance to the surroundings. They are costly to hand out and difficult for researchers to utilize. Though, the pollution diminution capability of those methods is reasonably fine but, the serious factors like high sludge production, supplementary time consumption, high requirement of manpower, and additional time requirement for final manufacturing product generation make them unviable. Comparing conventional treatment technology with hybrid treatment options on the basis of cost-effectiveness generates plenty of optimistic scopes for hybrid ideas. The hybrid technologies are exceedingly professional for contamination remediation from dye contaminated textile industry wastewater also derives ideas on the lesser need of operational resources. The maintenance cost, operating cost, capital cost and energy requirement, manpower need are lesser (comparing ratio of two treatment technology) in comparison with a single treatment system. The assumption of hybrid treatment options sometimes changes in specific cases with the manufacturing process being utilized, nature of raw materials, and complexity of used chemicals, the capacity of external power being imposed, and expertise of the operator. The foremost explanation behind the hybrid treatment option is more preferred are it shows immense opportunities for industrialists and researchers on the ground of treatment cost. This hybrid treatment option is more valid, reliable, and specific on the basis of cost-effectiveness.

5.3 Eco-friendly approach

Environmental degradation and its restoration preferences should be looked forward by modern scientist. The coupling of two or more than one treatment system is favorable from environmental perspectives as it consumes less energy and labor at the same time it is more efficient for pollution remediation from dye contaminated textile industry wastewater. Recent sciences need more certified treatment technologies favorable for ecosystem balance as well as pollution minimization. In this context, the hybrid treatment option is new innovative, cost-effective, less energy-consuming, and environmentally friendly treatment technology which is much needed for the recent environmental pollution scenario. This recent global scenario is fully dependant on new, novel treatment options where the expectation for high load pollutants could be easily minimized at the same time the hydrosphere imbalance could be avoided. The eco-friendly treatment system has been emerged by various scientists for years but, the success rate of these methods is very rare and in some specific cases these methods were unable to gain attention for implementation. The suggested option for dye contaminated textile industry wastewater is an advanced option for textile industry wastewater treatment and is capable of the full fill of such expectations.

Chapter 6: Conclusion and future recommendations

6.1 Conclusion

The majority of scientists welcome recent developments that are aimed at balancing the environment and reducing wastewater pollutants. But, it is quist difficult to handle these critical situations where anthropogenic and environmental negative activities are uncontrollable. Their impacts are massively degrading the water parameters which are required to be balanced for a sustainable environment. The current study has focused on using merged(coupling) treatment systems such as hybrid treatment systems. Using two or more methods is better for the environment because it uses fewer resources and manpower at the same time fulfills the limitations remained by a single treatment system. The high-intensity ultraviolet radiations were capable of the degradation of toxic chemicals bonding of dye contaminated textile industry waster and *C. pyrenoidosa* was more efficient for nutrient reduction. So, when both the treatment technology combined the treatment efficiency increased as compared to individual treatment technology. The specific concluding remarks of the results are given below:

- The pollution reduction was more efficient by immobilized algal cells than free algal cells; it's due to the availability of more surface area in immobilized alga in comparison to free algal biomass. The larger surface area enhances the adsorption process as it is directly proportional to the surface area of the adsorbate.

- The immobilized algal biomass reduced 46.7% of nitrate, 59.4% of phosphate, 83.1% BOD, and 83.0% of COD whereas; free algal biomass cell reduced 43.2% of nitrate, 56.7% of phosphate, 71.4% of BOD, and 78.0% COD.

- It was observed that with the increase in flow rate the pollution reduction increases, it's because the no of passes per unit time inside the reactor increases.

- There was a non-ideal flow behavior due to collision with immobilized algal cells while flowing in horizontal directions. But, this obstacle benefited the treatment efficiency. Because the contact time between immobilized algal cells and wastewater effluents increased due to such collisions which enhanced the pollution and color reduction efficiency.

- The estimated color reduction by solar energy-based treatment was 76%, and <98% by algal-based treatment.

- The application of hybrid treatment reduced the nutrient load like nitrate and phosphate by 52% and 63% respectively, at the same time color concentration by ≥ 98%. It was seen the reduction values of color concentration by designed hybrid setup was more as compared to both the individual treatment technologies.

- The COD reduction was 90% by using hybrid treatment whereas; 79% and 83% of COD reduction were obtained by solar energy and algal-based treatment respectively.

Though the pollution reduction and decolorization of dye wastewater were highly significant, complete degradation of dye contaminated textile industry wastewater compounds is not so easy due to the complex bonding of toxic chemicals. The recent physical and chemical technologies like coagulation, ozonolysis, advanced oxidation, membrane separation, and advanced methods like ultra-filtration are being used for dye contaminated textile industry wastewater. But, serious issues like cost-effectiveness, generation of secondary pollutants make them unfeasible. Again, single treatment technology is fully incapable of the degradation of this highly polluted textile industry wastewater. So, the combination of two or more of these treatment options can enhance the potential of reductions. It can be concluded that hybrid treatment system is the best possible approach which can degrade the high load pollutants as well as fulfill the gaps remaining in single treatment technology.

6.2 Future recommendations

Though the hybrid treatments system is one of the highly advanced treatment systems for wastewater treatment, it also has certain limitations. One of the major disadvantages of this treatment system is that the hybrid treatment system is dependent on electricity for its functions. So, longtime use of this system could demand high electricity. In this context, to fulfill this energy demand solar power could be one of the ideal options. Solar power-based electricity generation is so important and feasible these days that the hybrid setup could be designed in such a way so that solar energy-based electricity could be the best fit in that system. Thus, the whole hybrid system could be renewable energy-based cost-effective green technology. Besides this, the immobilized algae used for this study could be utilized for further experimental purposes. The algae used for the experiment could be collected and further used for multipurpose scientific studies like biodiesel production rather than merely leftover in the environment. Finally, it is recommended to deeply and carefully analyze all the process parameters (pH, temperature, dose and flow rate, *etc*) of the hybrid treatment system while implementing it on pilot scale.