Studies on the Thermal Energy Storage (TES) based Photobioreactor for Algal Biomass Production and its use for Different Biofuel Production

SUMMARY
of
THESIS

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SUMMARY

The global energy consumption increased rapidly with increase in world population, high living standard, and energy using patterns of the society. At present, the basic feedstock to produce commodity fuel is basically crude oil. The rapid depletion of this crude oil is now creating a pressure on transportation and aviation industry as well as environment in terms of pollution (CO_2, CH_4, and N_2O). Around the world noteworthy stepladder are being taken for a paradigm shift from today's petro-based refinery to biomass-based biofuel to sustain the green environment and global economy efficiently across the world. But, most of these emerging approaches are under technical risk due to large capital cost, less efficient, insignificant output. Researchers are focusing on advanced biomass cultivation technologies for biofuel production using different raw materials to produce a broad spectrum of main and co-products. In this context, the significant properties of algal biomass *i.e.* biochemical compounds (protein, carbohydrate, pigments, carotenoids, lipid, and fatty acids) and biofuels production (biodiesel, biohydrogen, biogas, and bioethanol) gained attention to focus on enhanced production of algal biomass. Algae as a production organism are being popular worldwide due to its multi-benefit approach and the functional bimolecular substances of algal biomass are of much concern due to its nutritional, medical, cosmetics, and pharmaceutical applications too. A relevant increment in algal based food and feed market has been seen due to the presence of high value chemical compounds *i.e.* fatty acids, colorants and vitamins, as a competitive with similar components produces from other sources. Therefore, large scale cultivation of algae are of great magnitude to increase the algal based green economy. In natural cultivation system as well as in artificial media, algae exposed to a number of environmental factors *i.e.* pH, light, temperature, nutrient, and carbon sources *etc.* out of which the accessible biogenic element concentrations are the most important parameters that affect algal growth. These variables (chemical and physical conditions) directly influence all the aspects of algal activity such as biomass productivity, specific growth rate, doubling time, metabolism intensity *etc.* The chemical and physical conditions of the algal culture system can be altered, which in turn have an effect on quantitative and qualitative growth of algal biomass. Additionally, there is a strong interrelationship between environmental factor and algal biomass growth rate. Therefore, process optimization of culture conditions efficiently enhances the yield of algal biomass production with desired metabolic products. The relative amounts of algal biomass production are directly linked to designing of photobioreactor, environmental, and nutritional condition including: the intensity of solar radiation, photoperiod, CO_2 concentration, pH, temperature, nutrients available (nitrate, phosphate, carbon), salinity, and hindrance of other microorganisms. In order to understand the synergistic interface between environmental/physical and chemical factors, optimization with multiple variables of these factors is required to develop high microalgal productivity. An effective PBR endow with all necessary conditions for algal biomass growth and development for efficient end products, is one of the major objective for this study. Apart from the shape of PBR, temperature is another key parameter affecting the productivity, this is also the part of present investigation, studied in coupling with designed reactor using wastewater as a substrate for algal growth nutritive material. Both type of macro/micro nutrients in wastewaters are found suitable for algal growth and simultaneously treating the wastewater also including heavy metal removal, as reported by various researchers in their recent researches. Benefits of this type integrated system includes: reducing the cost of wastewater treatment and scale-up the

biomass production on annual scale, less burden on freshwater resources and chemical media. Algal potential for synthesis of energy products can be enhanced by effective cultivation and harvesting system. Harvesting of algal biomass using advanced flocculants is also a significant part of this study. Effects of various parameters on harvesting efficiency of algal biomass (dose concentration, contact time, temperature, and pH) have been studied critically. Techno-economic assessment of designed bioreactor is compared with conventional reactor system using selected industrial wastewater from Common Effluent Treatment Plant (CETP) after primary treatment. Application of produced algal biomass for biofuel production also investigated in this research work. Therefore, keeping all these challenges in mind, designed objectives have been formulated in order to prove the concepts by experimental validations. Therefore, this research work has been divided into following chapters:

1. **Introduction and review of literature**
2. **Materials and methods**
3. **Phycoremediation of industrial wastewater and their impact on algal biochemical compounds using *Chlorella pyrenoidosa* with correlation study**
4. **Feasibility of thermal energy storage based photobioreactor for algal cultivation and biofuel production: a lab scale study**
5. **Comparative assessment of bioflocculant and chemical flocculants for algal biomass harvesting**
6. **Techno-economic analysis of TES based PBR for algal biomass and biofuel production: a comparative study**
7. **Conclusion and future recommendations**

Figure-1 is delineating the graphical abstract for the present research work, whereas Chapter wise summary of the present research work have been described in following sections:

Chapter 1: Introduction and review of literature

In this chapter, an overview of various process parameters (pH, light photoperiod, temperature, nitrate, and phosphate, carbon in salt form, carbon in gaseous form, wastewater, and photobioreactor) and their effect on algal biomass, biochemical compounds, and biofuel production have been described. Designing and fabrication of various photobioreactors, types of photobioreactors, construction materials, advantage and disadvantages, are also described. The wide application of algal biomass in various fields *i.e.* biofuel (biodiesel, biohydrogen, bioethanol, and biogas) and value-added products (protein, carbohydrate, pigments, and lipid) production is also discussed critically according to the literature available till date. After extensive literature survey, very limited number of researches are found on temperature based reactors to improve algal biomass cultivation particularly *Chlorella pyrenoidosa* with low-cost and low-energy intensive approach. Hence, a research framework has been outlined to save water and energy using *Chlorella pyrenoidosa* for this study with their fruitful end-products.

Chapter 2: Materials and Methods

The present chapter deals with experimental methodology and analytical techniques used to execute the experimental plan. This chapter explains about the selected algal strain, experimental plan with methodology used for each phases in this study. The analytical techniques used in present study are explained and basic information about microalgal culture and its growth optimization under different parameters such as pH, light photoperiod, nutrients (nitrate, phosphate, and carbon), and selected wastewater concentration (CETP wastewater) is also outlined. Experimental procedure adopted for wastewater treatment and parametric observations with heavy metal removal are also discussed. The fabrication of thermal energy storage based photobioreactor with specifications to enhanced algal production for biofuel/bio-oil production is also discussed in this chapter. Advanced harvesting techniques by using different flocculants (bioflocculant and chemical flocculant) to harvest produced algal biomass with analytical and kinetic tools are also a significant part of this chapter, which is experimentally investigated and discussed in chapter-3, 4, and 5 respectively. Techno-economic assessment of thermal energy storage based photobioreactor; wastewater (as nutrient source) and biofuel production have been critically assessed in chapter-6.

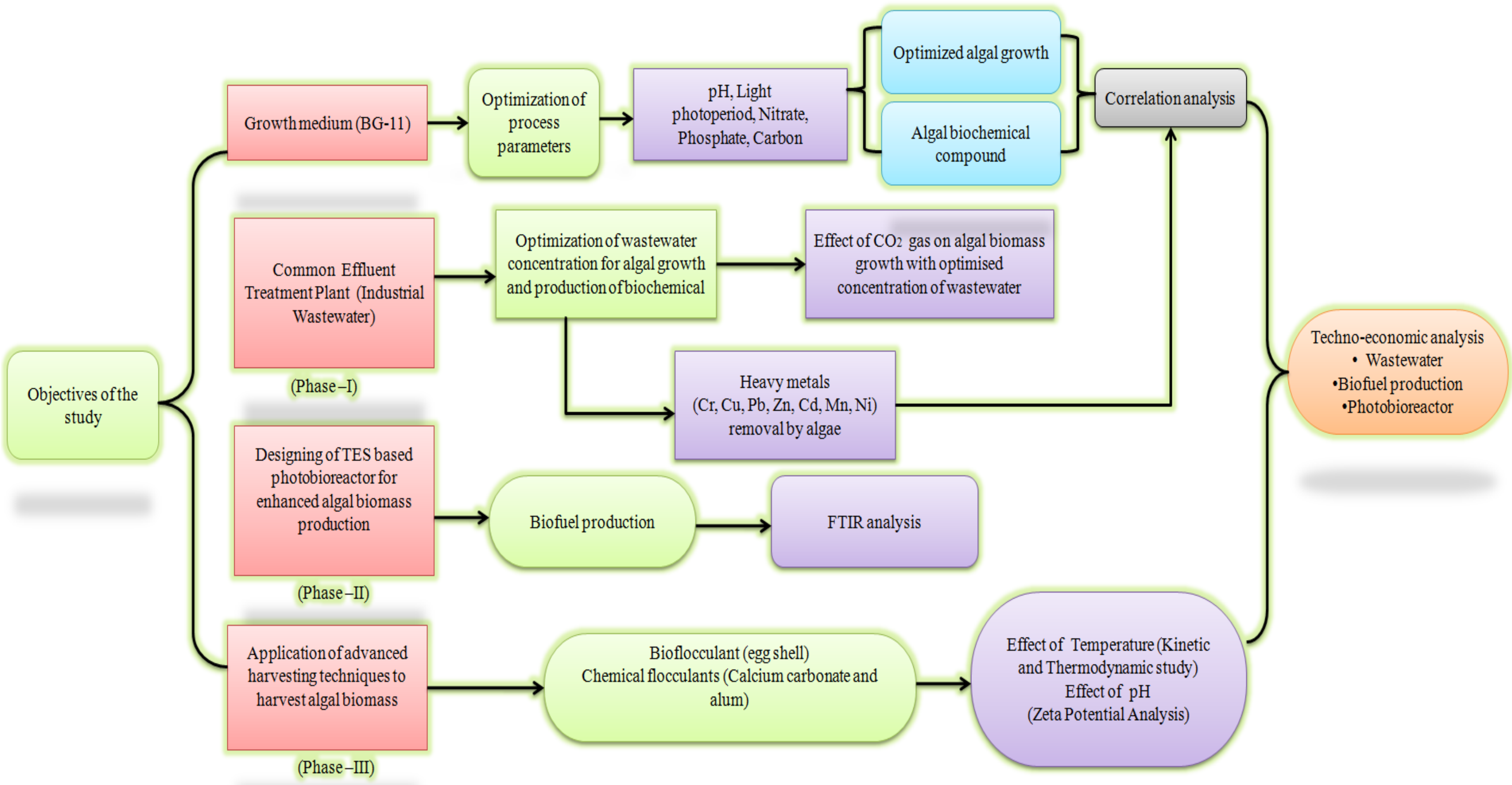

Figure 1: Graphical abstract for present research work

Chapter 3: Phycoremediation of industrial wastewater and their impact on algal biochemical compounds using *Chlorella pyrenoidosa*

The present chapter deals with optimization of selected process parameters (pH, light photoperiod, nitrate, phosphate, carbon in salt form, and carbon in gaseous form) and their impact on algal growth/production and biochemical compounds (protein, carbohydrate, lipid) have been performed with BG-11 medium. The present experimental result supports higher lipid production with low pH, nitrate, and phosphate, whereas high carbon concentration and 16L: 08D cycle of photoperiod supports higher lipid production. pH (7.5) was found as best medium for high biomass production. Lower pH was found suitable to induce higher lipid content (26.5±0.02 %). Optimized photoperiod 16L: 08D with maximum biomass (1.52±0.03 gL^{-1}) and lipid content (27.2±0.11 %). 0.4 gL^{-1} nitrate was found as best medium for high biomass (1.62±0.04 gL^{-1}) production. Lower nitrate concentration (0.05 gL^{-1}) was found suitable to induce higher lipid content (28.5±0.03 %). 0.1 gL^{-1} phosphate was found as best medium for high biomass production. Lower phosphate concentration (0.05 gL^{-1}) was found suitable to induce higher lipid content (25.5±0.06%). 0.2 gL^{-1} carbon concentration was found as best medium for high biomass production (1.76±0.07 gL^{-1}). Lower carbon concentration was found suitable to induce higher lipid content (26.4±0.09%).

Optimization of different concentrations (25%, 50%, 75%, and 100%) of wastewater collected from common effluent treatment plant has been done to investigate the optimum growth of algal biomass with efficient pollution reduction (organic, inorganic, and heavy metals) and algal biochemical compounds production. The relationship between different variables of process parameters and their effect on biochemical compound has also been studied by the application of statistical analysis *i.e.* Pearson correlation co-efficient analysis, which clearly describes the positive and negative correlation between parameters and biochemical compounds.

The effect of CO_2 with optimised concentration (50%) of CETP wastewater has also been investigated to examine algal biomass productivity and its impact on algal biochemical compounds. Algae based CETP wastewater treatment was found to as effective way for reduction of pollutant load and heavy metal. Among various selected concentration of CETP wastewater, alga showed its best growth at 50%, however, *Chlorella pyrenoidosa* also found to tolerate the higher concentration (75% and 100%). Algae showed its best growth at 25% and 50% concentrations, however algal biomass also found to tolerate the higher concentration (75% and 100%) with less productivity. Algal affinity to uptake metal was found highest for Cr (VI) followed by the Zn, Cu and Pb. 50% test solution was found with maximum biomass productivity (1.4±0.07 gL^{-1}) and lipid production (27.6±0.015 %). The Pearson correlation co-efficient analysis supports with positive correlation with carbohydrate in 100% test solution whereas, it was found negative with protein and pigments (chlorophyll '*a*', chlorophyll '*b*', and total chlorophyll) with these concentrations *i.e.* 50%, 75%, and 100%. The experimental results found significant with different concentrations of CO_2 treatment to *Chlorella pyrenoidosa*. Maximum biomass productivity was obtained (2.09±0.08 gL^{-1}) with 50% test solution of CETP wastewater with 15% CO_2 supply (gaseous form). Lipid productivity (26.5±0.05) obtained maximum at 5% CO_2 supply. Maximum rate of CO_2 sequestration was obtained at 10^{th} day with 15% of CO_2 supply *i.e.* 5.8 gCO_2 L^{-1} D^{-1} by *Chlorella pyrenoidosa.* Hence, optimization of process parameters is very significant tool to enhance biomass and lipid productivity with *Chlorella pyrenoidosa* using CETP wastewater as nutrient media in comparison to other chemical based media sources.

This is an integrated technology treatment technology for clan environment and energy options (algal biomass to biofuel approach).

Chapter 4: Feasibility of thermal energy storage based photobioreactor for algal cultivation and biofuel production: A lab scale study

In order to investigate the efficiency of photobioreactor for algal biomass production, two different type of reactors have been designed and fabricated *i.e.* horizontal tubular photobioreactor (TPBR) and thermal energy storage based vertical column PBR (TES based PBR), specifications used for these are summarized in Table 1.

4.1. Horizontal tubular photobioreactor

A closed horizontal Tubular Photobioreactor (TPBR) was fabricated to execute this experimental study. The bioreactor consisted of six transparent glass tubes, conjoined with a reservoir (storage tank) of 20L storage capacity of algal media. An electric motor pump was incorporated in the system for continuous circulation of algal cell suspension. An aerator was also inserted in the reservoir for gaseous exchange and to maintain the uniform distribution of nutrients throughout the algal media. Tubular photobioreactor for cultivation of algal biomass was designed and fabricated to enhance/dense production of biomass whereas, 50% concentration of CETP wastewater taken as nutrient media for algal biomass growth and development. BG-11 medium was taken as control to analyse the algal productivity and growth rate comparatively.

4.2. Vertical column photobioreactor

Three separated PBR setups were prepared and run in parallel to investigate the temperature of the algal medium *i.e.* uncontrolled PBR/without PCM or thermostat (PBR-I), controlled PBR with PCM (PBR-II), and controlled PBR with thermostat/electric coil (PBR-III).

Table 1: Specifications for photobioreactors selected for study

Horizontal Tubular Photobioreactor	
Description	Specifications
Material	Glass
Number of tubes	Six (06)
Diameter	0.1m
Length	1m
Total volume	20L
Working volume	10L
Motor	0.5 Horsepower
Vertical Column Photobioreactor	
Material	Glass
Total volume	10L
Working volume	5L
Aeration	Aqua air pump motor
Light source	LED of 20 watt
Temperature sensor	Thermometer
Radiation measurement	Solar power meter (wm^2)
pH measurement	pH meter
PCM (Phase Change Material)	Capric acid (3 kg)
Control condition	Thermostats (maintained 30°C in PBR)

The experiment was run for 13 days to get maximum biomass production of selected algae (*Chlorella pyrenoidosa*). The PCM was selected on the basis of temperature range required for *Chlorella pyrenoidosa* (25-30°) with respect to weather temperature profile of Lucknow (study area) during winter season, where the experimental work was carried out. The temperature was maintained in winter season with minimum 10°C and maximum 25°C recorded in a day. The temperature of PBR system was obtained near ambient temperature during experiment in PBR-I. Accordingly, there is a need to select the PCM having melting temperature in range of

30-35°C. Based on these considerations, an organic PCM was selected as suitable candidate *i.e.* Capric acid ($CH_3(CH_2)_8COOH$) of analytical grade to maintain the temperature of the PBR to enhance the algal biomass. The melting point of this PCM was 31.5°C, and latent heat was 36.23 Jg^{-1} respectively. A three chambered vertical column PBR was setup with 5L working volume fabricated by using transparent glass material. Each chamber was equipped with thermometer and motor based-aerator, to check the temperature of the PBR to maintain uniform distribution of nutrient in algal media. Three separated PBR setups were prepared and run in parallel to investigate the temperature of the medium with PCM and without PCM. Side and back portion of the system were insulated by using 2 cm expandable polystyrene sheets to prevent the transfer of heat to and from the surroundings. The changes in temperature inside PBR-I, II, and III were recorded continuously from 6:00 am to 12:00 pm at regular interval. The PCMs were needed to charge thrice a day from 6:00 am to 12:00 pm. Temperature plays an important role to enhance the algal biomass and algal based bio-oil production. It is very important to find the most suitable way to enhance the temperature of the medium without algal cell structural deformities. The present chapter is focused to enhance the temperature of the medium in PBRs for biomass cultivation as well as heavy metal removal with bio-oil production. TPBR was efficient to produce (≈22 gm) dry algal biomass but the total amount of produce biomass cannot be harvested due to large amount of biomass remain stuck on reactor's tube wall.

Whereas, in PBR-I (without TES-based system) algal biomass was obtained not in significant amount (1.3 gm) as the optimum temperature was not provided to the system, as a result, decrease in biomass and bio-oil (11.4%) production with nominal metal removal (48.1±0.03%) rate with ambient temperature in the range of 5 to 18°C. Although, in PBR-II, significant amount of algal biomass (15.4 gm) was produced as the temperature of system was maintained by phase change material to its optimum required temperature *i.e.* 25-30°C. 41% algal oil was obtained from PBR-III using n-hexane method. In PBR-III, 15.9 gm of total biomass was obtained with significant amount (35%) of algal oil production. So, algal growth is very much dependent on type of reactor used either at lab-scale or large-scale with optimised conditions. Furthermore, temperature maintenance is very much controlled in designed TES-PBR for *Chlorella pyrenoidosa*.

Findings of the present study support a long term sustainable approach for algal biomass harvesting during unfavourable climatic conditions. Among various types of closed PBR, two different types of closed PBRs (tubular photobioreactor and TES based PBR) are studied in this research study. It has been found that close type reactors are supported to prevent/minimise contamination and prevention of water loss. Similarly, thermal energy storage based PBR (PBR-II) is an novel approach for algal biomass cultivation, which supports approximate five times higher biomass productivity even in adverse climatic conditions (low temperature). Use of CETP wastewater as a culture medium also supports the phycoremediation approach (heavy metal removal) in PBR-II system.

Chapter 5: Comparative assessment of bioflocculant and chemical flocculants for algal biomass harvesting

The present chapter mainly emphasised to investigate the effect of various flocculants (bio and chemical flocculant) with respect to other parameters (dose concentration, contact time, temperature, and pH) to harvest algal biomass significantly. The experimental results of this chapter reveal the significant use of bioflocculant (waste egg-shell) (100 mgL^{-1} concentration) with optimized time (30 minutes) and temperature (40°C), which provides better harvesting efficiency (HE) with respect to *Chlorella pyrenoidosa* without any cells surface structural deformities. Compared to inorganic flocculants, it is cheap and does not impart harmful impact on the algal Cell. These studies also disclose that temperature also plays an important role to achieve better harvesting efficiency. The experimental data is proven by the pseudo second-order kinetics model and thermodynamic functions. The experiment provides an economically viable, proficient, and expedient green approach to harvest algal biomass *i.e. Chlorella pyrenoidosa*. The advantage of this approach has been observed with maximum flocculation efficiency *i.e.* 99% without any algal cell surface and structural deformities. The present method showed sustainability with operational simplicity to overcome the hurdles arising in harvesting of algal biomass with maximum efficiency to promote large scale application (bioenergy and biomaterial) from harvested algae. Maximum HE (99%) was found to be associated with 0.0 mV of ζ value with pH 4.0 for bioflocculant, which was relatively higher than the Laboratory available Calcium Carbonate (LACC) *i.e.* 95% at pH 8. This observation concludes highest HE of bioflocculant at its isoelectric point, which represents the least stable colloidal system. Whereas, ζ value for LACC indicated the unstable colloidal system on selected pH ranges. Furthermore, bioflocculant was found non-toxic without structural deformities in comparison to LACC. Hence, it's an economically viable, proficient, and expedient green approach to harvest algal biomass using waste egg shell with sustainable chemistry for biomass harvesting.

Chapter 6: Techno-economic analysis of TES based PBR for algal biomass and biofuel production: a comparative study

Techno-economic assessment was done on the basis of selected wastewater (CETP) as nutrient substrate for algal biomass production and fabricated TES based PBR for enhanced algal production. A theoretical assessment has been made using CETP wastewater on the basis of per day and annual wastewater discharge capacity for algal biomass and biofuel production potential. Only two different concentrations (50% and 100%) of CETP wastewater were selected for algal biomass production and biofuel production on the basis of wastewater production and treatment simultaneously as presented in Table 2. 50% concentration of wastewater was selected on the basis of maximum biomass production (1.4 gL^{-1}) and lipid content (27%) and pollution load removal at lab-scale, although with 100% concentration results were found not significant but predicted values of biomass and lipid suggest that it may be a solution of treatment when we are discharging the wastewater without treatment in surroundings. So, this can be a sustainable integrated approach for waste minimization with biofuel production simultaneously. Here, total algal growth period taken as one cycle, completed in total 15 days (*i.e.* life cycle of selected algal biomass). It means algal biomass was harvested at interval of 15 days in total 300 working days (maximum days of working) of plant. According to some previous and our experimental results minimum to maximum only 70 to 75% of lipid can be converted to crude bio-oil. This conversion efficiency totally depends on various process parameters (pH, temperature, light, and nutrients) and on growth parameters for species selected for the study. Although theoretical findings of biomass production and lipid productivity were found good enough for Lab to Land approach but storage of wastewater on per day basis is a big challenge on practical scale. So, this area is a part of future research, here we can suggest pits formation for collection of wastewater on industrial discharging sites or at CETP location before treatment.

Furthermore, Table 2 describing the predicted total biomass and biofuel production with CETP wastewater if used/coupled with designed TES-PBR at large scale, here experimental findings with TES-PBR-II system (Chapter-4) were used to calculate the results. Here, algal biomass collected/harvested on the basis of 13 days /cycle (*i.e.* life cycle of algal biomass) during ambient temperature of (5 to 18°C) and PBR-I, without PCM (5 to 15°C), but reactor temperature was controlled up to (25 to 30°C) with phase change material to enhance algal growth during adverse temperature condition. TES-PBR is significant to produce optimum algal biomass productivity even in extreme cold condition, as the temperature of the PBR-II is controlled by phase change material. Temperature fluctuation is a big challenge to cultivate algal biomass throughout the year. North region of India faces two to four month of winter season. Whereas, cold climatic regions cross the world (temperate, tundra, and taiga) faces moderate to extreme cold conditions. Therefore, it is difficult to cultivate algal biomass in extreme worst conditions. But, TES based PBR is a novel/efficient/ potential approach to enhance algal biomass and biofuel productivity even in unfavourable climatic condition (particularly temperature fluctuations). Similarly, if we plan algal biomass production at commercial scale for cold climatic regions and winter season in tropical regions, TES based PBR will provide an efficient results for biomass based biofuel production. The maximum algal biomass production with PBR-I (without TES based PBR) and II (with TES based PBR) are 0.85 gL^{-1} and 4.8 gL^{-1} respectively with unfavourable conditions (temperature fluctuation). Algal biomass production in PBR-II is higher with favourable condition (temperature range 25°C-30°C) than PBR-I where the condition was unfavourable (low temperature). If we compared the biomass productivity of PBR-I with PBR-II total production has been increased 5.6 times higher. Therefore, it is possible to enhance the algal biomass productivity in present fabricated PBR with optimum biomass and biofuel production. Residual biomass after bio-oil extraction also has a potential to produce biogas as a bioenergy option, however, dried algal biomass without any processing in integration with wastewater (dairy) also used for biogas production. The maximum annual biomass productivity with 50% concentration of CETP wastewater predicted 16150 kg but with TES based PBR (PBR-II) it increases five times (91200) even in adverse climatic condition (6 to 15°C). Lipid content of *Chlorella pyrenoidosa* is also enhanced 27% to 35% with PBR-II, as culture system. Therefore, techno-economic assessment of any system should be a part of research and development for sustainable and economically feasible way to produce algal biomass based biofuel and other (nutritional supplement, cosmetic products, medicines *etc.*) value-added products.

The economic analysis of TES-PBR is carried out by supposing that system can easily work in 300 days in a year and annual cost of fuel to produced hot water for 65 days is done by electric coil/gas burner. The Figure 2 showing the comparative annual cost and fuel cost for TES-PBR with auxiliary systems *i.e.* Electric Coil based Photobioreactor (EC-PBR) and Gas based photobioreactor (GB-PBR). Basis on the basic specifications of considered systems and economical parameters of Indian market the greatest value of annual capital cost (1420 INR) and annual cost of fuel (882 INR) is evaluated for EC-PBR. The values of annual capital cost (390 INR) and annual cost of fuel (157INR) becomes lowermost for TES-PBR with auxiliary system. Basis on the basic specifications of considered systems and economical parameters of Indian market the greatest value of annual capital cost (1420 INR) and annual cost of fuel (882 INR) is evaluated for EC-PBR. The values of annual capital cost (390 INR) and annual cost of fuel (157INR) becomes lowermost for TES-PBR with auxiliary system. The price in INR for the production of hot water/litre by considered systems is also calculated. It was found from Figure 3 that the price of hot water/litre by TES-PBR with auxiliary system, EC-PBR and GS-PBR are INR 0.07, 0.26 and 0.29 respectively.

Table 2: Actual and Predicted biomass and lipid production with CETP wastewater on per day basis discharge

CETP wastewater concentration	Biomass productivity	Lipid productivity (%)	Predicted Biomass Production (*MLD)	Annual Predicted Biomass Production (kg)	Predicted Lipid Production (%) (*MLD)	Annual Predicted Lipid Production (*MLD)	Biodiesel production (*MLD) (70 % conversion)	Annual Predicted Biodiesel production (70 % conversion)
Biomass and biofuel at favourable conditions naturally (with optimum required temperature)								
50%	1.4 gL^{-1}	27	2660 kg/cycle	53200 kg	718	14364	502	≈10054.8
100%	0.3 gL^{-1}	12	570 kg/cycle	11400	68	1368	47.6	≈957.6
Biomass and biofuel production with TES based PBR (PBR-II)								
**50%	4.8 gL^{-1}	35	9120 kg/cycle	91200	3192	31920	2234	22340
Biomass and biofuel production with TES based PBR (PBR-I)								
**50%	0.85 gL^{-1}	35	1615 kg/cycle	16150	565	5650	395	3950

4(* 1.9 MLD discharge of CETP wastewater; ** Annual discharge calculated with maximum working days of 300 **Annual production with respect to TES based PBR, 1 cycle = 12 days, total number of cycle per year 10, 4 months have been considered with temperature fluctuations in winter season)

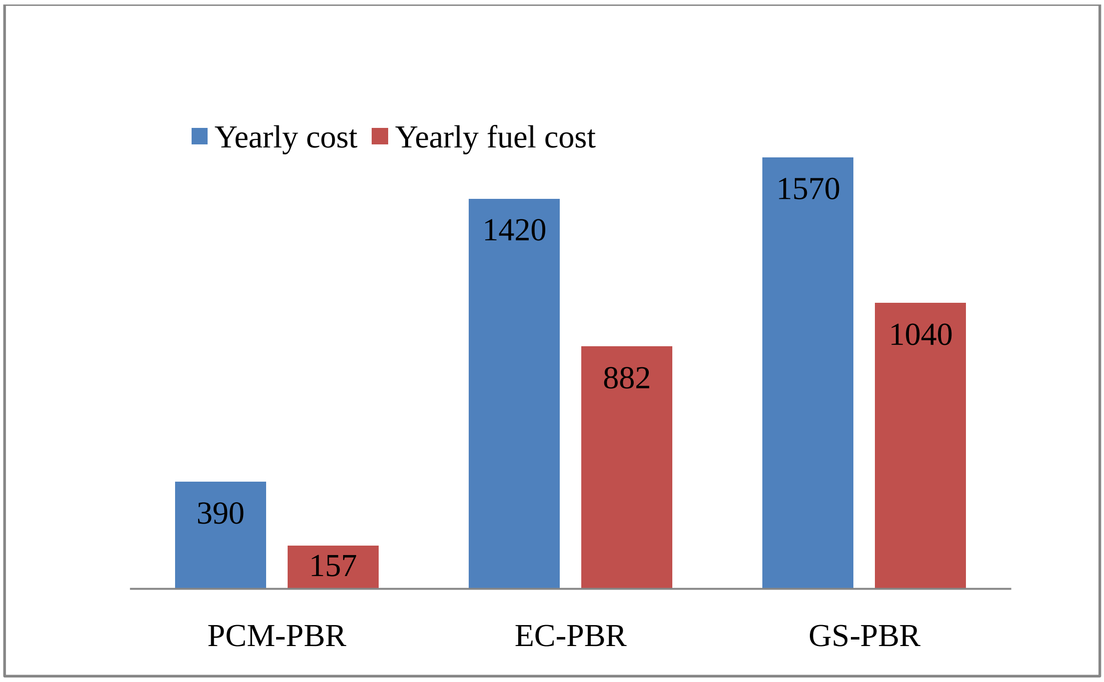

Figure 2: Comparison of yearly cost and yearly fuel cost of different systems

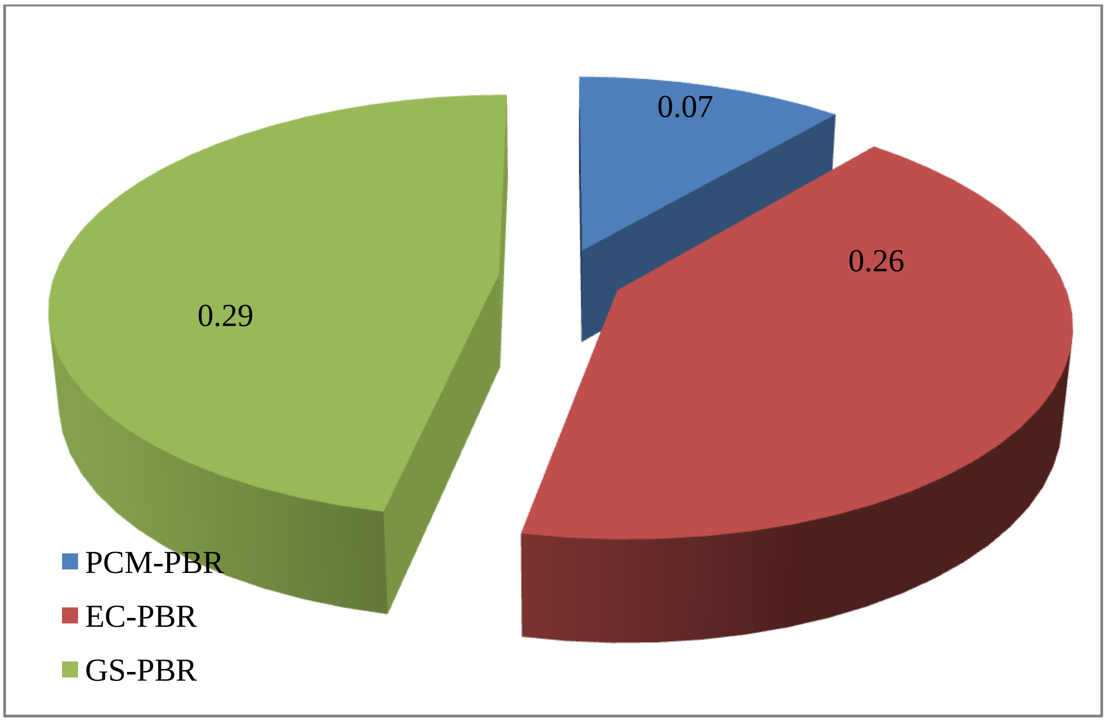

Figure 3: Comparison of cost of production of hot water/litre by considered systems

Chapter 7: Conclusions and Future Recommendations

In view point of objectives decided for this thesis, all work has been successfully completed by its experimental validation. The experimental results were significantly analysed by using algal growth kinetics and Pearson correlation coefficient between process parameters (pH, light photoperiod, nutrients *i.e.* nitrate, phosphate, carbon in salt and gaseous forms) and algal biochemical compounds (protein, carbohydrate, pigments, and lipid) to analyse positive or negative correlation between these variables. Optimization of CETP wastewater to obtain maximum algal growth with efficient wastewater treatment (in terms of physico-chemical and metals removal) through selected algal species *i.e. Chlorella pyrenoidosa* is a significant part of this research work. Average removal rate kinetic was applied to investigate the affinity of algal biomass for metal uptake. Impact of different concentrations of CO_2 with optimised concentration of CETP wastewater has also been studied in Phase-I of experiment. Designing of thermal energy storage based photobioreactor for enhanced cultivation of algal biomass and biofuel production coupled with optimised parameters obtained from Phase-I of experimental study was carried out in Phase-II. Phase-III of experimental study emphasised on advanced algal biomass harvesting techniques with optimization of various parameters *i.e.* dose concentration, temperature, and pH. The experimental data has been supported by Pseudo-second order model, thermodynamic function, and zeta potential analysis.

From the experimental studies, examined and evaluated, the finding are clearly conclude that research efforts, particularly with low capital cost, operating cost, and lifespan of reactor is the demand for large-scale cultivation system. Furthermore, use of wastewater for algal growth as a nutrient media may also be potential alternative for treatment option which may further be used for bioenergy options (biodiesel, biogas, biohydrogen *etc.*) although whole processing system efficiency depends on selection of algal strain and its compatibility with composition of wastewater selected. Similarly, role of bioreactor in coupling with algal strain and wastewater is an important physical structure to support for large cultivation of biomass. Simultaneously, algal biomass used for treatment of wastewater can further processed for bio-diesel (bio-oil) and deoiled biomass can also be used for biogas production again in co-digestion with nutrient rich wastewater as a raw material.

7.2. Future recommendations

Although, this novel thermal energy storage based system has been experimentally investigated but it needs further research on the basis of factors like, light distribution, mass transfer, heat transfer from phase change material to media to maintain the temperature of photobioreactor and enhance algal growth rate at very low/high ambient temperature. Use of other phase change materials suitable for algal biomass growth, should also be investigated in future research. Similarly, use of different nutrient rich wastewater with other selected algal strains should also be the part of future research studies for treatment as well as biofuel and other value added end products. Lipid content also has a large variability with different types of algal species, if grow with different media sources (chemical media/wastewater resources as a media) may also be recommended for future work. Furthermore, techno-economic feasibility of each adopted technology should also be assessed to make it commercially accessible for sustainable bio-economy in long-term.