Chapter 7

Cost Benefit Analysis of LED's application for the microalgae cultivation process

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7.1. Introduction

The cost analysis of LEDs for microalgae cultivation was previously carried out by Blanken et al. 2013 [595]. Nevertheless, no recent reports dealing with LEDs cost and energy balance analysis have been found. The cost calculation in the present work is based on the theoretical approaches and data obtained from the previous literature. The current research projects an estimated value for the industrial-scale biomass production, considering the current conversion rate, which is 1 USD = Rs. 74.17 as of August 2020. Therefore, there may be variations in the real-time situation as it may be challenging to maintain the constant yield of biomass on light ($Y_{x/ph}$) because the light source's efficiency decreases linearly with time. Initially, the cost analysis is based on the values of input parameters required to calculate LEDs electricity and investment cost. Microsoft Excel 2016 and MATLAB (ver. 2017b) were used to perform the necessary calculations and plot the functions.

7.2. Cost Benefit Analysis

7.2.1. Input parameters for electricity and investment cost

The initial calculation considers electricity cost for the production of 1 kg of dry microalgae biomass (in dollars per kg of dry weight biomass, USD kg^{-1} DW). The cost of electricity requires following (i) Electricity price for industries (ii) Biomass yield on light ($Y_{x/ph}$); (iii) Light efficiency. In India, every state has its own electricity unit rate. The average price of electricity (0.11 USD kWh^{-1}) has been used in the calculation [596]. The $Y_{x/ph}$, 1 g-DW mol-ph^{-1} was assumed to be the realistic aim of industrial-scale biomass production. This assumption was based on the calculation shown in ref. [595]. The efficiency of the light source is estimated through PAR efficiency. HID lamps, LED light and LED light compact having

PAR efficiency 1.87 μmol-ph s^{-1} W^{-1}, 3 μmol-ph s^{-1} W^{-1} and 3.6 μmol-ph s^{-1} W^{-1} were considered for the calculation [597].

The cost required for the installation of the lights, the lifetime of the light source and $Y_{x/ph}$ are input parameters for the calculation of investment cost of the LEDs. The light source's price is based on the cost required to emit 1 μmol-ph s^{-1} (Table 7.1) by the HID lamps and LED lights. The WPE of the LEDs decreases linearly with time and the accumulation of dust affects its efficiency. LEDs's lifetime is around 25,000 hours, with 90% WPE and 50,000 hours with 70% WPE [597]. Life is only about 12,000 hours with 90% WPE for the HID lamps. Generally, LEDs are replaced after 10,000-15,000 hours of utilization [595]. The value of Yx/ph will be the same, i.e., 1 g-DW $mol\text{-}ph^{-1}$.

7.2.2. Calculation of electricity and investment cost

Eq. (7.1) and (7.2) have been used to calculate the investment and electricity cost in USD kg-DW^{-1} of microalgal biomass and results have been shown in Table 3 and Figure 2.

$$Investment\ costs = \left(\frac{Cost\ light\ source}{lifetime * Y_{x/ph}}\right) \tag{7.1}$$

$$Electricity\ costs = \left(\frac{electricity\ price}{PAR\ efficiency * Y_{x/ph}}\right) \tag{7.2}$$

where, the cost of the light source is in USD (μmol s^{-1})$^{-1}$, life is in hours, $Y_{x/ph}$ is biomass yield on light (g-DW $mol\text{-}ph^{-1}$), electricity price is in USD kWh^{-1} and PAR efficiency is in μmol-ph s^{-1} W^{-1} [595].

Table 7.1. Investment and electricity cost calculation for LEDs during microalgae cultivation process.

		HID	LED		LED
		(Current Study)	Blanken et al. (2013) [595]	(Current Study)	Compact (Current Study)
Input Parameters	Initial PAR efficiency (μmol-ph s^{-1} W^{-1})	1.87	1.91	3	3.6
	Average PAR efficiency (μmol-ph s^{-1} W^{-1})	1.68	1.67	2.7	3.3
	$Y_{x/ph}$ (g mol^{-1})	1	1	1	1
	Life (Hours)	12,000	50,000	50,000	50,000
	Output loss over lifetime (%)	90	70	70	70
	Electricity price (\$ kWh^{-1})	0.11	0.11	0.11	0.11
	Investment Cost {\$ (μmol s^{-1})$^{-1}$}	0.27	1.34	0.7	0.8
Calculated Cost	Total Electricity cost (\$ kg-DW^{-1})	18.18	19.3	11.31	9.25
	Total Investment cost (\$ kg-DW^{-1})	6.25	7.4	3.88	4.44

Total cost ($ kg-DW^{-1})	25.3	25.3	15.19	13.69

(Conversion factor: 1 hr = 3600 sec)

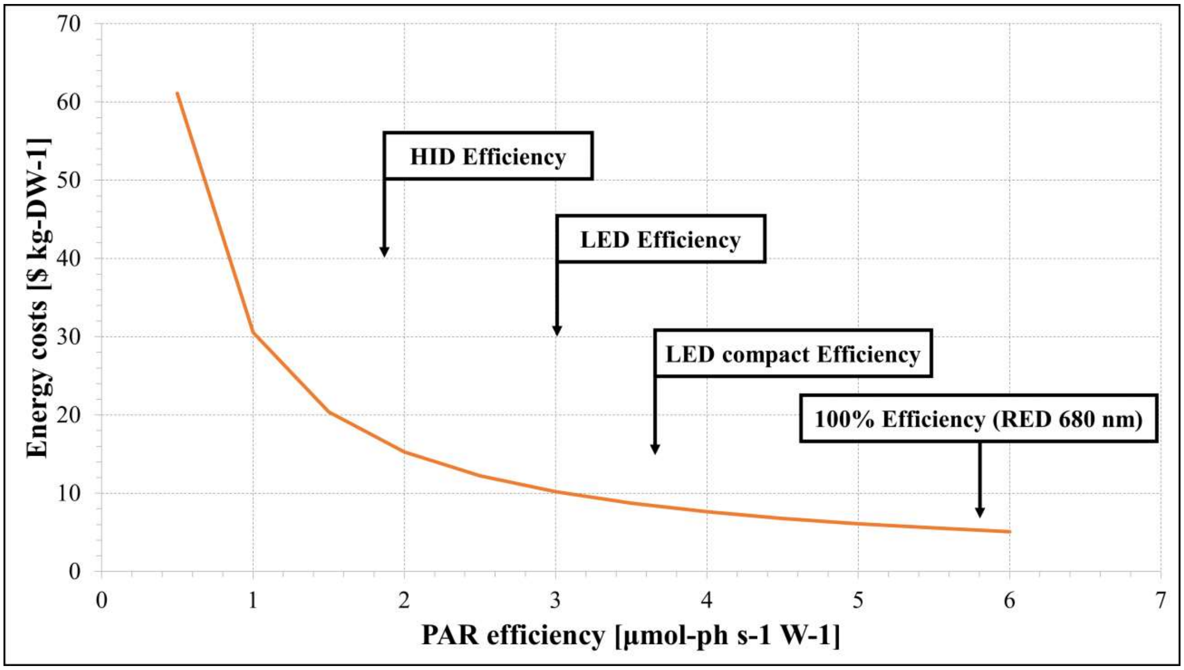

Figure 7.1. Variation in energy cost ($ kg-DW^{-1}) with the PAR efficiency (µmol-ph s^{-1} W^{-1}).

It is apparent from Table 7.1 that the total cost of the LEDs application has decreased by 40 - 50% compared to the cost calculated by Blanken et al. (2013) over 7 years. Previously, LED lighting was an expensive source of light as compared to HID. At present, LED incurs 40% less electricity cost than the HID. The rationale behind the decrease in the cost is the increase in LED's PAR efficiency up to 3.6 µmol-ph s^{-1} W^{-1} [597]. Now, the application of LEDs for microalgae cultivation is far more economical than HID [595].

Moreover, the advantages of LEDs such as narrow emission peak, small dimension, no infrared light emission and the extensive availability of wavelength, make LEDs a better choice for microalgae cultivation than HID. The investment cost of LEDs has also decreased by 40%. The main factor contributing to the decrease is the reduction in installation cost (50%

reduction). There has been no significant improvement in the lifetime of LEDs, it remains the nearly same as previously reported [595]. Therefore, increase in the lifetime of LEDs is the main challenge in order to decrease the investment cost. Though the cost of LED lights has decreased as compared to previous years yet its application for low-cost products is not economical. The main focus areas for the reduction of total cost can be towards enhancement in PAR efficiency and lifetime of LEDs. It may be expected that the cost of LED lights will decrease further in the coming years and its application for microalgal cultivation will be more economically feasible for the products having low-value such as biofuel.

The focus can also be on improvement of the $Y_{x/ph}$ and biomass productivity in addition to enhancement in PAR efficiency of LEDs and reduction in the investment cost. Literature review suggests that $Y_{x/ph}$ is enhanced by optimizing the growth parameters such as light, temperature, optimum nutrient level and proper harvesting techniques [598], [599]. Temperature directly affects the cell's metabolic activities, water equilibrium, intracellular enzyme activity and gas solubility [221], [223], [600]. The value pH influences nutrient availability in the medium and enzyme activity [601], [602]. Photoperiod plays an essential role in for the evaluation of growth rate of cell and lipid content [577]. Thus, the growth parameters are needed to be optimized for increasing the biomass yield. Such optimization operations can only be carried out in bioreactors that are controllable and can be adjusted at the optimized growth conditions [603].

7.3. Energy balance analysis

Energy balance analysis of the microalgae cultivation process by applying LEDs is based on electrical energy supplied during the cultivation process and the total energy output in the form of chemical energy stored in microalgal biomass. Eq. 7.3 was used for the estimation of energy efficiency.

$$\boldsymbol{Energy\ Efficiency} = \frac{\boldsymbol{Total\ Output\ Energy}}{\boldsymbol{Input\ Electrical\ Energy}} \times \mathbf{100} \qquad (7.3)$$

The chemical energy stored in the microalgal biomass was calculated on the basis enthalpy of combustion of the algal biomass, which was found to be 0.48 MJ C-mol^{-1} as per ref. [604], [605]. The input electrical energy was calculated from the light's PAR efficiency with the help of data obtained from publication [595]. Based on the LEDs' current PAR efficiency (3 - 3.6 μmol-ph s^{-1} W^{-1}), input electrical energy was 5-8 MJ C-mol^{-1}. The microalgae cultivation process's energy efficiency was found to be nearly 6-8% (Eq. 7.3). It is noteworthy to mention that the microalgae cultivation process's energy efficiency has been almost doubled in recent years, but still, it is low [595]. On the contrary, India's thermal power plant's current efficiency for electricity generation is 30-50% [606]. Thus, a huge amount of energy is lost during the microalgae cultivation process. Hence, it is not advisable to use LEDs for low-cost products.

7.4. Approaches for reduction in the cost of AL

Some approaches for reduction in the cost of the microalgae cultivation process with the aid of LEDs include applying green energy such as wind and water for supplying the power to the artificial lights [607]. However, these systems suffer from the issues of less energy storage [595]. The following approaches have been proposed for their integration with the microalgae cultivation process for better conservation of energy in addition to decrease the cost of LEDs (i) application of Arduino based automated control system (ii) photovoltaic powered PBRs (iii) application of additional light. Some of the approaches have been discussed in the scientific literature. Still, more research is needed for complete implementation in the microalgae cultivation process.

7.4.1. Arduino based automated control system

Arduino platform was launched in 2005, which provides an open-source platform for electronic software and hardware. It is one of the most fast-growing, easy to implement and less expensive electronic prototypes applied to develop control devices [608]. The Arduino based microcontroller application in microalgae cultivation has been previously suggested by Wishkerman et al. (2017) [609]. The authors designed an automatic Arduino-based system to produce a flashing light effect coupled with different colors of light. Arduino platform can be used to build an automated, low-cost control system with a Light-Dependent Resistor (LDR) sensor coupled with microcontrollers which will be used to operate LEDs by turning them on or off during the cultivation process. The resistance of the LDR sensor depends on the intensity of light in the environment. Its resistance decreases with an increase in light intensity and vice-versa [610]. Based upon that, it sends a signal to Arduino based microcontroller. The detailed working of this control system has been explained in the upcoming section.

7.4.1.1. Working of the proposed Arduino based automated control system

The schematic diagram of the Arduino-based automated control system for controlling the current supply to LEDs is shown in Figure 7.2.

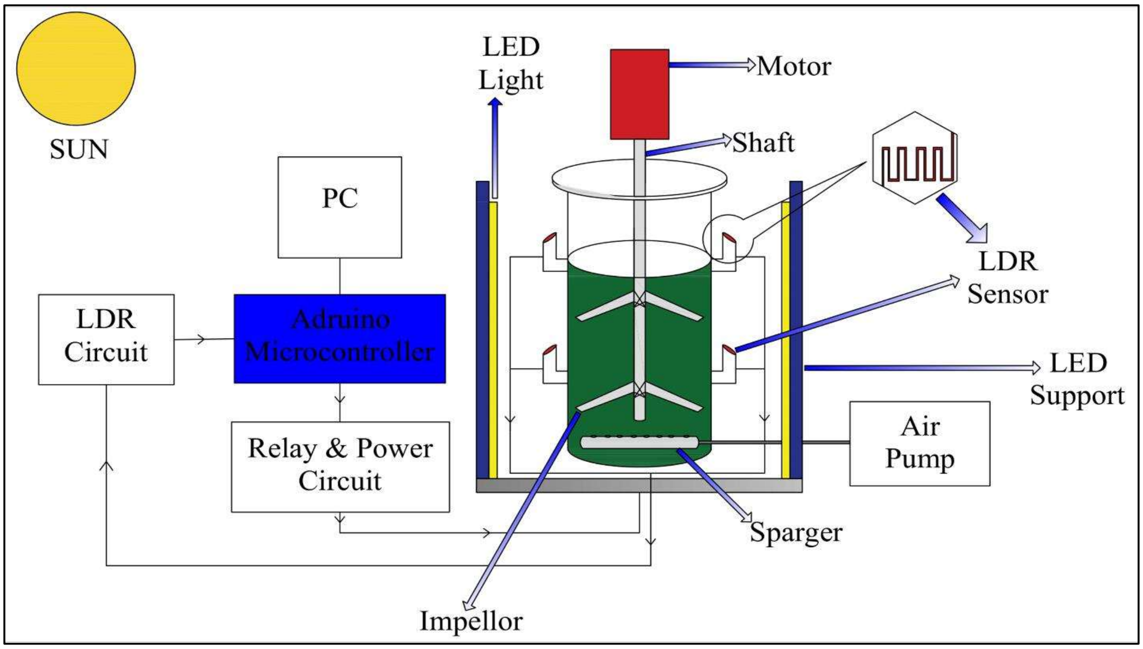

Figure 7.2. An automated control system having an LDR sensor and Arduino microcontroller for controlling the power supply to LEDs. (Designed in AUTOCAD 2020: Student Version)

As shown in Figure 7.2, 4 LDR sensors are fitted on the walls of the photobioreactor. These LDR sensors will send the signal following the intensity of sunlight to the LDR circuit. LDR circuit will further process the signal and pass it to the Arduino microcontroller. The microcontroller processes the signal depending on the light intensity's set point and sends the on/off signal to the relay and power circuit. Relay acts as a control switch and supplies the power from the power circuit to the LED light depending on microcontroller's signal. When there is enough intensity of the sunlight above the set point, the system turns off the LED light. But, if the intensity of sunlight decreases below the setpoint, such as during evening or bad weather, the system turns the LED light on, thus supplying light continuously. This automated controller will drastically decrease AL's cost as electricity supply to the LEDs will only be required when the intensity of sunlight is low or unavailable.

7.4.2. Photovoltaic powered photobioreactors

The focal thought behind the development of a photovoltaic powered photobioreactor was to develop self-cooling PBRs with the generation of electricity by harvesting sunlight and improving energy balance of microalgae production system remarkably [611]. The harvested energy can be further used for supplying power to LEDs. These PBRs can control the temperature without an external heat exchanger and harvest the solar energy, thereby decreasing significantly the net input energy to the PBRs. The use of photovoltaic material in the microalgae cultivation system was first proposed by Moheimani and Parlevliet (2013) [612]. The system utilizes a spectrally selective and semi-transparent photovoltaic (PV) filter placed above the PBRs in the microalgae cultivation plants. The proposed system transmits only a specific spectral range of light, preferably in the PAR region, to the PBRs and captures the rest for transmitting it to PV cells for electricity generation. The generated electricity can then be used to supply energy to LEDs if solar intensity is low and for other reactor operations. This proposal paved the way for the design and construction of insulated glazed photovoltaic (IGP) PBRs that are spectrally selective and can harness energy for electricity generation [613], [614]. The IGP PBRs consist of a transparent PV panel of Cadmium telluride (CDTe) thin film with low emissivity (low-e). The PV panel is fixed in the upper part of the PBR and a low-e film is mounted on the illuminated surface. This low-e film allows more than 70% selective PAR transfer to the microalgal culture while simultaneously it reflects and blocks more than 90% of infrared and ultraviolet radiation. The back reflection of the non-PAR keeps the reactor cool and thus eliminates the need of heat exchangers [614].

Nwoba et al. (2020) installed IGP PBRs on 1-ha area and developed a pilot-scale microalgal cultivation system for *Nannochloropsis* biomass production. This cultivation system had no external heat exchanger. Authors showed that the installed PV panels could generate up to 1126.8 GJ ha^{-1} yr^{-1} (equivalent to 313.0 MWh ha^{-1} yr^{-1}) electrical energy, which reduced the net energy demand. Moreover, these reactors showed a 73% greater net energy ratio (NER) than the conventional reactors [611]. The low emission film can be modified to pass only light of a specific wavelength from the sunlight. Thus, a two-stage culture strategy can be easily performed. In the first stage film only passes red/ blue spectrum of the sunlight to increase biomass productivity. After the growth period, film is replaced by another film that allows only the green spectrum to increase lipid productivity. This system works more efficiently in tropical and sub-tropical countries like India where the sunlight is available for most of the year. These IGP PBRs may also be coupled with the Arduino based automated control system, where the electrical energy harvested by the PV cells supplies current to the LEDs when solar intensity is low or unavailable.

7.4.3. Application of additional light

Another approach includes the application of additional LEDs in addition to the currently applied LED for the cultivation of microalgae [603]. It is regarded as a cost-effective method and can be easily implemented. A decrease in biomass yield was observed when the light intensity increased above the light saturation point [615]. The authors assumed that when the additional light is applied, there is a decrease in the $Y_{x/ph}$ by 25%. Authors also showed that AL's cost decreased by 14 to 15% when additional FL was applied [603]. More decrease in cost can be obtained if the FLs are replaced with LEDs.

7.5. Future Perspectives

LEDs have now become the first choice for designing photobioreactors and have gained significant momentum in algal biotechnology. Their special characteristics, including unique spectral properties, the broad availability of wavelength, small size and less heat dissipation, favour the application of the LEDs in photobioreactors as compared to HID and FL. The climatic simulation of the PBR and various LED technologies can be adequately harmonized which will allow the better adaptation of algae cultivation. Research focussing on culture strategies, including the effect of multiple LEDs, two-stage culture, PWM and AM is scarce and needs to be investigated. The design of IIPBR was started in early 1990. However, its application was limited due to its expensiveness. The focus was mainly on low-cost products such as biofuel and less expensive reactors such as raceway ponds. However, in recent years the decrease in the cost of LEDs and the increase in focus towards the high-value products are making research and development of IIPBR more feasible. The availability of light is also more in IIPBR than externally illuminated PBR. These are even used to produce low-cost products in various reactor configurations such as bubble columns and tubular reactors [616]. The modifications like reducing the light loss by using waveguides and optimizing surface to volume ratio and temperature are needed for IIPBR. More research in IIPBR will surely replace externally illuminated PBR, especially for the production of high-value products.

Results of the cost and energy analysis indicate that there has been a significant decrease in both electricity and investment cost of the LEDs which makes its application for microalgae cultivation more economical. However, it is not suitable for the large-scale cultivation of microalgae for low-cost products as both input cost and energy loss during the cultivation process is high. A surge in the PAR efficiency, lifetime and light-dependent biomass yield by optimizing the culture parameters will further decrease the cost of LEDs. PAR efficiency can be improved by increasing the number of PAR photon emissions per second or by decreasing the input power requirement. Low voltage technology will also help in enhancing the LEDs efficiency. The approaches for decreasing cost of LEDs seem to be widely effective even for large-scale cultivation of microalgae. NER of photovoltaic powered photobioreactors can be further improved by optimizing the culture conditions and PV panel's optical properties for better entrapment of sunlight and increasing its energy conversion efficiency [611]. Modifying the low emission panel to implement a two-culture strategy will increase biomass and lipid productivity. They will prove to be boon for the remote areas where there is no proper facility of electricity and fresh water for cooling PBRs.

7.6. Conclusions

The microalgae cultivation process running solely on LEDs and compact LEDs incurs a total cost of 15.19 USD kg-DW^{-1} and 13.69 USD kg-DW^{-1}, respectively which has been decreased by 40-50% from the previous years. But, keeping in view of low-cost products, LEDs application for microalgae cultivation is not practically feasible. The energy balance analysis also showed that efficiency of microalgae cultivation utilizing artificial lights is around 6-8% which indicates that energy efficiency is needed to be improved substantially.