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Bio-jet Fuel from Microalgae: Reducing Water and Energy Requirements for Algae Growth

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ABSTRACT *- Cost-effective production of environmentally safe aviation fuel by partially replacing diesel and kerosene in jet fuel blends with biodiesel produced from microalgae is highly desirable. Biodiesel is a clean burning, environmentally-friendly alternative fuel that could be produced from domestic resources like algae. Its use as a jet fuel blend will reduce sulfur emission, particulate matters and will mitigate greenhouse gas emission. It will also increase the security of energy supply and support the development of jobs and rural communities. This project focuses on reducing energy requirements and fresh water usage in order to achieve the lowest cost of algae bio-jet fuel blend production. Light Emitting Diodes as a light source for algae growth have a major advantage of saving energy and resulted in producing higher biomass algae. Waste water and reverse osmosis water were compared. RO water was more effective in algae growing. The effect of fluorescent light intensity on the algae growth rate was studied. An approximate relation was developed in which the rate algae growth is proportional to the square root of the light intensity.*

Keywords *– bio-jet fuel, Chlorella Vulgaris, LED algae growth, photosynthetic efficiency, carbon sequestration*

I. INTRODUCTION

1.1 Airline Industry Challenges: The airline industry is experiencing growth in air travel demands [1]. Aircraft engines are efficient in fuel use. The energy intensity in terms of Btu per passenger is lowest for rail followed by airline [1]. Upon combustion, the aircraft jet fuels produce carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NOx), carbon monoxide (CO), oxides of sulfur (SOx), unburned or partially combusted hydrocarbons, particulates, and other trace compounds. The airline industry consumes over 5 million barrels of oil per day worldwide. This is placing challenges for the industry to ensure security of fuel supplies, address environmental challenges and minimize global warming effects. Renewable jet fuel for the aviation industry, also termed bio-jet fuels obtained by biofuels (e.g., biodiesel) blending seems a good approach.

1.2 Aviation Fuel (Jet Fuel): Table 1 shows different types of commercial and military jet fuels. Light jet fuels (kerosene) are refined from distillation of crude oil in the presence of a catalyst. There are two main grades of fuel in commercial aviation: Jet A-1 and Jet A, both are kerosene type fuels. Jet B is a blend of gasoline and kerosene (a wide cut kerosene) but it is rarely used except in very cold climates. JP-5 and JP-8 are chemically enhanced fuels with antioxidants, dispersants, and/or corrosion inhibitors to meet the requirements for specific applications.

Table 1 Types of Commercial and Military Jet Fuel.

Civil/Commercial Jet fuel	Military Jet Fuel
Jet A-1: Kerosene grade suitable for most turbine engine aircraft. Flash point above 38°C (100°F). Freezing point maximum of (-47°C). Net heat of combustion minimum of (42.8MJ/kg) **JET A**: Kerosene type of fuel. Flash point above 38°C (100°F) Freezing point maximum (-40°C) **JET B**: Distillate covering the naphtha and kerosene fractions. Freezing point maximum of (-50°C). Net heat of combustion minimum of (42.8MJ/kg). Higher flammability. Significant demand in very cold climates.	**JP-4:** The military equivalent of Jet B with the addition of corrosion inhibitor and anti-icing additives. **JP-5**: High flash point kerosene. **JP-8**: The military equivalent of Jet A-1 with the addition of corrosion inhibitor and anti-icing additives.

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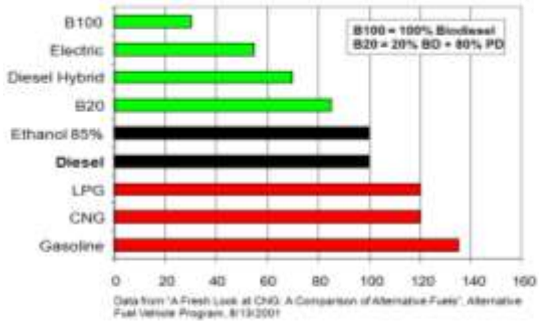
1.3 Biodiesel: Solar to chemical energy conversion through microalgae can produce biodiesel**,** which is an alternative, renewable diesel fuel made from vegetable (e.g., algae) oils or animal fats rather than petroleum. It is biodegradable, nontoxic, and drastically reduces most emissions from a diesel engine, is far safer to use and transport, and can be used in existing diesel engines with little or no modification. It can be used as pure fuel (termed B100) or in a blend with petroleum Diesel (e.g., B20 is 20% Biodiesel + 80% diesel). Figure 1 shows that B100 or B20 releases less CO_2 than gasoline, diesel and other fuels. Chemically, biodiesel is a mixture of Fatty Acids Methyl Ester (FAMEs) produced from the catalytic transesterification reaction of triacylglycero



[1]. Figure 1: Relative Greenhouse Gas Emissions of Different Fuels

TAGs (vegetable oil or fatty acids) with methanol [2]. The catalyst could be an acid or an alkali [3], [4], and [5]. In most applications sodium hydroxide or potassium hydroxide is used. These are less expensive and result in faster transesterification rate compared to acids catalysts and biocatalysts [6]. The challenge in biodiesel production is to find enough low-cost vegetable oil feedstock to result in favorable techno-economic analysis [7] and produce biodiesel at a comparative cost to diesel.

1.4 Food vs. Energy Crops: Currently, vegetable oils from food crops such as soybean, canola, and palm are the feedstock to make biodiesel. However, this has created significant worldwide opposition due to the increase of food price and growing food shortage, which resulted in food strikes worldwide. Also, food based crops are a dispersed source of energy, requiring large land area to produce the needed oil feedstock. For example, soybean, canola and palm produce only 50, 90 and 650 gallons of biodiesel per acre per year, respectively [8] and [9]. To produce enough biodiesel from soybean to cover the annual consumption of jet fuels (Jet-A, JP-5, etc.) in the US, a very large area of the entire arable land area of the US would have to be used. This also creates environmental concerns such as ozone depletion due to N_2O emitted by fertilizers, acidification of soil due to sulfur and nitrogen oxides from fertilizers and eutrophication and algal blooms due to pesticides [10]. The UN Food & Agriculture Organization (FAO) is asking researchers to redirect biodiesel production to the use of non-edible crops. Hence interest has turned to non-food based feedstock such as microalgae.

1.5 Microalgae: Microalgae oil is a promising biodiesel feedstock being researched. It is produced from oil-rich (or lipid-rich) microalgae (or simply algae). Algae can produce 5,000-15,000 gallons of biodiesel/acre-year [11], [12], [13] and [14]). Microalgae are single cell microorganisms and most of them live in aquatic habitat such as sea, rivers and oceans [15]. They require water rich in nutrients, CO_2 and photonic energy to grow and convert water and CO_2 to oils. Once the grown algae is harvested and dried, Oil is extracted from the microalgae and used as feedstock for biodiesel production. The left-over microalgae biomass (after oil extraction) can be Fermented to alcohol, or can be used as a source of protein for cattle.

1.6 Photobioreactor: The enclosure where the algae can grow. It can be an open pond or an enclosed container in which algae grow at set conditions without concern about contamination. This can be as simple as a lab scale conical transparent glass beaker exposed to light in which air is bubbled or a more sophisticated industrial scale reactor. The challenge is to achieve cost-effective high algae oil production rate, e.g., using less fresh water, energy and nutrients.

1.7 Marginal Land Use: Microalgae do not require soil for growth and can be grown in closed photobioreactors on marginal land. This offers productive use of land that presently yields few economic benefits, and reduces the worldwide conflict with food crops. This is attractive both ethically and financially. It is estimated that one quadrillion Btu (Quad, or 7.5 billion gal.) biodiesel could be produced from microalgae on 200,000 hectare (500,000 acres) of desert land (rapeseed crop would require 21 million hectares) [16].

1.8 Nutrients. Algae are ideally grown in water around 75°F [17]. Algae growth is affected by two key nutrients; nitrogen, N and phosphorous, P. Limitations in N or P can slow down algae growth. The nutrient solution contains macronutrients (N, P and sodium) and micronutrients. If any of these nutrients exist naturally in the water used to grow algae it will provide an economic advantage.

1.9 Water Challenges: The world is on the brink of an unprecedented water crisis. The UN estimates that by the year 2025, 2 out of 3 people will not have access to drinking water. Water, rather than land, scarcity may prove to be the key limiting factor for biofuel feedstock production [18]. To produce one gallon of biodiesel the water required has been estimated to be; Soybean: 15,600 gallons of water, Canola: 5810 gallons and microalgae: ~300-1000 gallons [19]. Clearly, microalgae have better water footprint, yet they are still considered water-costly. Using seawater or impaired water (e.g., wastewater) would reduce the water footprint of bio-jet and will not contribute to the worldwide water crisis.

1.10 Carbon Dioxide: Algae require about 45 pounds of CO_2 to produce a gallon of biodiesel [20], or 6.2 kg CO_2/kg biodiesel. For large scale microalgae production, the flue gases from power plants (or similar industries like cement) would be ideal. An average 500 MW power station emits roughly 400 tons CO_2 per hour. The use of CO_2-rich flue gas will have the added advantage of recycling the major greenhouse gas, CO_2, and may have an economic benefit if a carbon credit is established.

1.11 Microalgae Biodiesel: The viscosity of vegetable oils and microalgae oils are usually 10 (or more) times higher than that of jet fuel (1.2 cSt), [21] and [2]. Raw algae oils can damage existing jet engines, clog filters due to their high viscosity. The transesterification of algae oils reduces the original viscosity [2] and [8].

1.12 Advantages of Blending Biodiesel with Jet-fuel: The production technology used in this research is shown in Figure 2. It involves algae growth, harvesting, oil extraction and transesterification to biodiesel. The biodiesel will be blended with Jet A (or JP5) and diesel to produce bio-jet fuel blend that can be used on a diesel engine. The US Navy has accepted bio-JP-5 as an alternative to JP-8 fuel. Biodiesel is non-toxic, contains no aromatics or sulfur, and is more biodegradable and safer to handle than diesel or jet fuels. Also, biodiesel adds lubricity to the fuel. The strong advantage of using biodiesel is the improvement in the emission of particulate matter (PM).

Figure 2: Bio-jet fuel production by the blending process

II. Technical Challenges

2.1 Greenhouse Gas Emission: Aviation contributes about 2.7% of the US national greenhouse gas inventory. Global estimates are at about 3% with the majority coming from commercial aviation. It is predicted that by the year 2025 the aircraft greenhouse gas emissions in the U.S. will increase 60%. The combination of higher air travel demands, energy security, uncertainty in crude oil prices and desired reduction in greenhouse gas emission are motivating the transition to alternative renewable carbon-neutral jet fuel blends. Recent studies compared the CO2 emission of different fuels relative to Jet fuel [22]. It was concluded that the two promising fuels that lower the relative CO2 emission are bio-jet fuel and liquid hydrogen (H2) from water.

2.2 Heating Value: Jet fuel should have the lowest mass per unit energy and the lowest volume per unit energy. H2 mass per unit energy is about 36% of bio-jet fuel (22.73 kg/GJ or 52.86 lb/Million Btu). However, H2 has the highest volume per unit energy of 436% of bio-jet fuel. The present work focuses on liquid bio-jet as a reasonable near term fuel, with an aim of using microalgae as a source of oil feedstock to biodiesel to be blended with jet fuel, as shown in Figure 2. Boeing estimated that biofuels could reduce flight-related greenhouse-gas emissions by 60 to 80 percent.

2.3 Indoor Algae Growth: Algae are autotrophic, i.e., they require light energy to photosynthesize. Algae use the light radiation between 400 and 700 nm [23] (as a reference, the wavelengths of Red and blue lights are 650 and 475 nm respectively). This spectrum region is called "Photosynthetic Active Radiation" (PAR). 43% of the solar radiation is in PAR. The light intensity is often expressed as the photon flux density (PFD), i.e., the number of photons impinging on a flat surface per unit of time, micromole/m^2s. Algae studies are usually done indoors using artificial illumination under carefully controlled conditions. The simplest and least expensive light sources are "white" fluorescent lamps, which were used in the present study. Light-emitting diodes (LEDs) tend to emit in a very narrow emission band. LEDs are very robust, have longer life-expectancy, lower heat generation, greater tolerance for switching on/off and lower energy consumption than fluorescent bulbs.

2.4 Project Objectives: In order to reduce the energy requirements, CO2 emission to make the process greener, and the fresh water requirements the following objectives were defined:

- Investigate replacing Fluorescent light with LEDs.
- Compare algae and oil production in fresh vs. municipal waste water.
- Study the effect of light intensity on algae and oil production

III. METHODOLOGY

3.1 Algae Growth: Chlorella vulgaris was studied in the present work.
Vulgaris is characterized by faster growth and easier cultivation than other microalgae. Hence it is a promising resource for biodiesel production. The Vulgaris was cultivated in 4 L bubbling fish tank PBRs continuously exposed to 2×34 W (68 W) fluorescent daylight at room temperature, as shown in Figure 3. Light intensities of 2000 and 8000 Lux were used to study the effect of light intensity on microalgae growth. Each experiment lasted 18 days.

Figure 3: Experimental setup for microalgae growth.

Two microalgae mediums were used; reverse osmosis (R.O.) water and municipal wastewater. The algae growth was monitored by measuring the solution optical density (absorbance) at 660 nm, and by cell counts. Once the algae are grown they are harvested, centrifuged and freeze dried to obtain algae flakes. The flakes were ground to powder and massed to obtain the dry algae production rate in mg dry algae/L-day. Hexane solvent was used to extract the oil (lipids) from the dry algae. The oil was massed to determine the oil content in g oil/ (100 g dry algae) and the oil productivity in mg lipids/ (L of solution-day).

3.2 LEDs: LEDs are expected to reduce the electric energy requirements of large-scale algae production and the CO2 emission associated with the generation of electricity. The light absorption by microalgae has a spectral distribution over the PAR. It is important to select the LED colors to have the highest absorbance by the algae. Figure 4 shows the spectral distribution of the absorbance of green algae (like Vulgaris) over the PAR wavelengths 400 – 700 nanometers [23]. The strongest absorption is in the blue (around 470 nm), followed by red (650-680 nm). The LEDs tested in the present work were flat square panels (1 ft x 1ft) of red LEDs and of combined red and blue LEDs. Each panel was rated 14 W. Two panels (28 W) were used for each fish tank photo bioreactor. The measured LED light intensities were maintained at 2000 Lux. This allowed comparison of LEDs and fluorescent light operation.

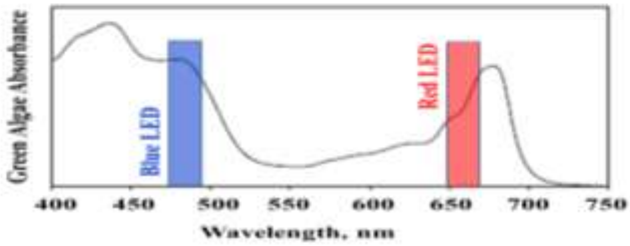


Figure 4: Spectral distribution of green algae absorbance.

3.3 Data Analysis/Calculated Indicators: The performance of the PBRs was established by calculating the indicators explained in Table 1.

Table 1: Performance Parameters and Definitions [25], [26], [27] and [28]

Parameter	Definition/How Calculated
Photosynthetic/light capture efficiency is the light energy transferred through PBR and converted to biomass.	Ratio of the energy produced by the combustion of the algae to incident light energy produced by the artificial lights used.
Carbon Sequestering/Capture Efficiency is the mass of C sequestered by the algae relative to the C supplied to the PBR.	C in dry algae formed/ Total C from the air into the PBR during growth, assuming: constant air flow rate, air CO2 (394 ppmv) is the only C source, and dry algae are 60.4% C, based on literature.

IV. RESULTS/DISCUSSION

4.1 Daily Algae Solution Absorbance: The growth medium optical density (OD) or absorbance was measured every two days with a spectrophotometer to monitor algae growth. Figure 5 shows the variation in the light absorbance over the 18 day growth period. Two sources of water medium were used, R.O. and wastewater. Three different light sources are compared; white/daylight fluorescent, red LEDs and red-blue LEDs. Microalgae grown with fluorescent light had the lowest absorbance, around 0.5 after 18 days. The use of red or red-blue LEDs show up to 5 times increase in the measured absorbance. Algae growth in wastewater using red and blue LEDs reached an absorbance of 1.5, compared to 2.5 for algae grown in R.O. water. The results show that the use of wastewater to save fresh water looks promising.

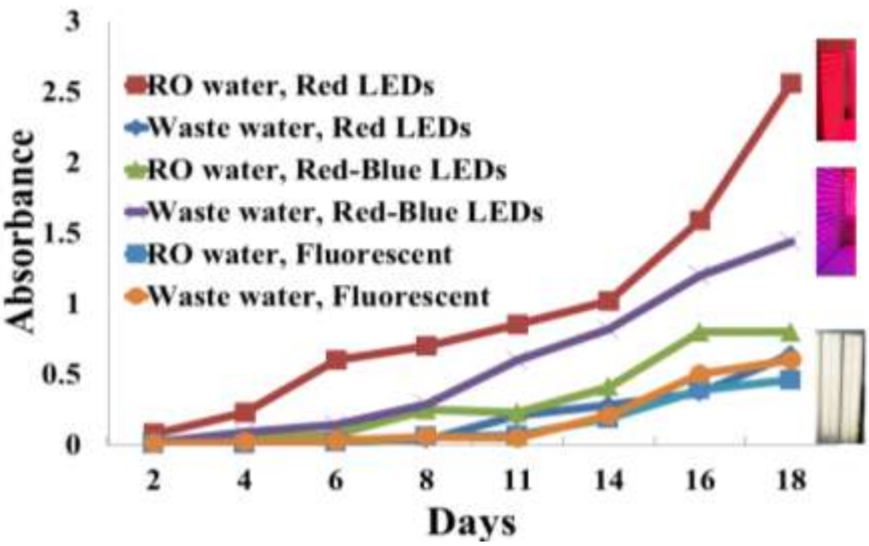


Figure 5: Effect of Light Source (White Fluorescent, Red LED and Red-Blue LED at 2000 Lux) on Vulgaris algae growth in RO water and Waste water

4.2 Dry Algae Biomass after harvesting and drying. Figure 6 shows the effect of the 2000 Lux light source (White Fluorescent, Red LED and Red-Blue LED) on the dry algae production rate, mg dry algae/L-day, for R.O. water and wastewater at the end of the 18 day growth period. The178 mg algae/L-day algae production rate in R.O. water using red-blue LEDs is 100% higher than using the white (daylight) fluorescent bulbs (88 mg algae/L-day). Similar trend was observed for algae growth in waste water; red-blue LEDs are 30% more productive than fluorescent. The Figure shows also the effect of the growth medium source on the algae production rate using Red-Blue LEDs. The 91 mg algae/L-day algae production rate in waste water is 50% of the 178 mg algae/L-day in RO water. These results show that waste water is a promising medium for algae growth.

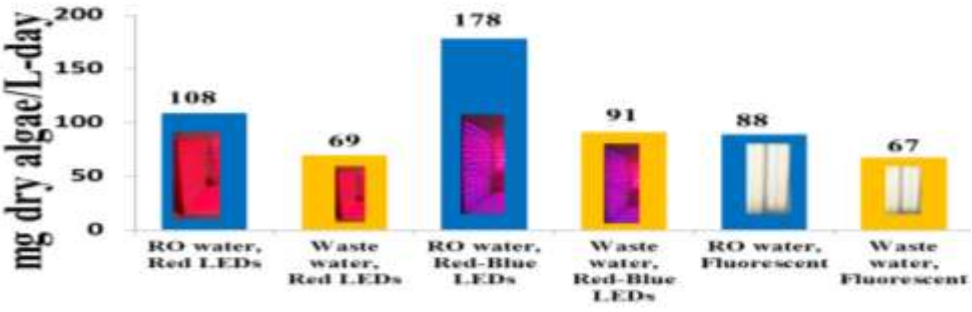


Figure 6: Effect of Light Source (White Fluorescent, Red LED and Red-Blue LED at 2000 Lux) on algae production rate in RO water (blue bars) and waste water (yellow bars) at the end of 18 day growth period.

4.3 Algae Oil: Figure 7 shows the effect of the 2000 Lux light source (White Fluorescent, Red LED and Red-Blue LED) on the algae oil (lipids) content, g lipid/100 g dry algae for R.O. water and wastewater at the end of the 18 day growth.

Algae growth in R.O. water and fluorescent light resulted in 1 g oil/100 g dry algae, the lowest value. The results show that the oil content of algae grown in wastewater using red LED had 85% of the highest value of 7% obtained using RO water and red-blue LEDs. The combination of red-blue LEDs and waste water yielded 4% oil content, or: 58% of the R.O. water and red-blue LEDs.

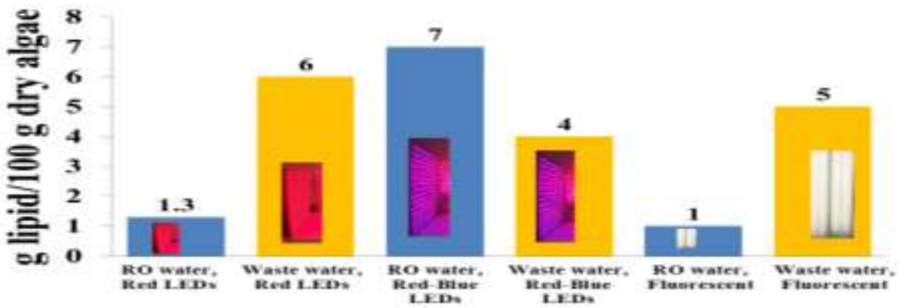


Figure 7: Effect of Light Source (White Fluorescent, Red LED and Red-Blue LED at 2000 Lux) on algae oil content in RO water (blue bars) and waste water (yellow bar)s at the end of 18 day growth period.

4.4 Light Capture and Carbon Capture Efficiencies. The data collected were used to calculate the photosynthetic/light capture efficiency and the carbon capture/ sequestration efficiency. The results are plotted in Figures 8 and 9. Figure 8 shows that the light capture efficiency was between 3.6% (waste water medium and red LEDS) and 8.4% (R.O. water medium and red-blue light). Using waste water medium and red-blue LED the 4.7% light capture efficiency is about 56% of the maximum value of 8.4% of R.O. water medium and red-blue light.

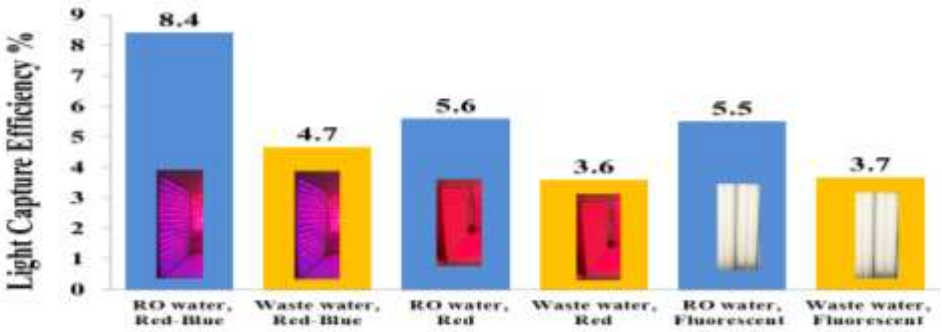


Figure 8: Effect of Light Source (White Fluorescent, Red LED and Red-Blue LED at 2000 Lux) on algae light capture (or photosynthetic) efficiency in RO water (blue bars) and waste water (yellow bars) at the end of 18 day growth period.

Figure 9 show that the carbon sequestration efficiency of the microalgae was between 3.4% (R.O. water white fluorescent lights) and 8.6%. These values are in agreement with published data [25], [26], [27], [28], [29] and [30].

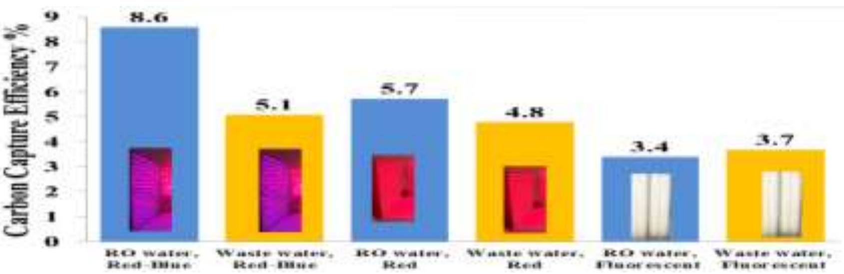


Figure 9: Effect of Light Source (White Fluorescent, Red LED and Red-Blue LED at 2000 Lux) on algae carbon capture efficiency in RO Water (blue bars) and Waste water (yellow bars) at the end of 18 day growth period.

4.5 Effect of Light Intensity on Growth Rate & Lipid Content. The effect of light intensity on the growth of algae and the production of oil were studied using white fluorescent light. 2000 and 8000 Lux intensities were selected. Figure 10 shows the resulting effect of the light intensity on the growth of algae in R.O. water and in waste water. The results show that the daily algae growth rate (r) almost doubles with the four times increase in light intensity (I) for both media.

Figure 10: Effect of white fluorescent bulbs light intensity on algae growth in RO water (blue bars) and waste water (yellow bars) at the end of 18 day growth period.

The data-fitted equations are

$r = 2 \sqrt{I}$ for RO water

$r = 1.52 \sqrt{I}$ for waste water

where r is the daily algae growth rate in mg dry algae/L-day and I is the light intensity in Lux. The square root relationship agrees with research on light-cured adhesive. It was found that the curing speed was proportional to the square root of the irradiance being absorbed [31].

Figure 11 shows the effect of white fluorescent light intensity on the lipid production rate, in mg oil (or lipids) per liter of algae growth solution per day. Both R.O. water and waste water show increase in the algae oil/lipids production rate. However, the algae oil production improvement in waste water from 1.34 to 5.14 mg oil/L solution-day is 33% of RO water (from 0.88 to 8.14 mg oil/L solution-day).

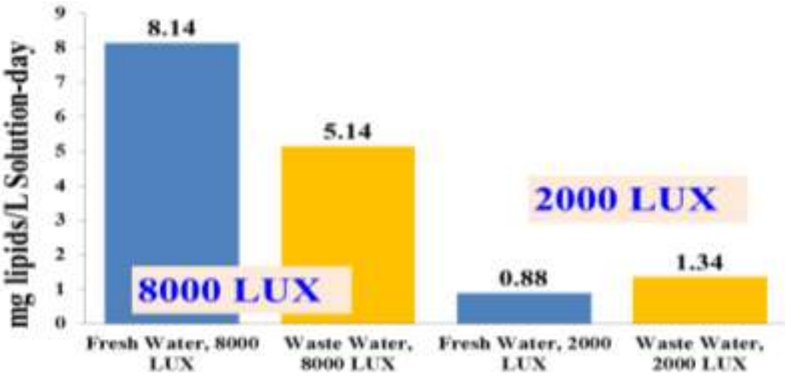


Figure 11: Effect of white fluorescent bulbs light intensity on algae growth in RO water (blue bars) and waste water (yellow bars) at the end of 18 day growth period.

V. Conclusion

Successful growth of Chlorella Vulgaris was achieved in reverse osmosis (R.O.) medium and waste water medium (which would reduce the fresh water foot print of algae oil production) using three different light sources, white fluorescent, red LEDs and red-blue LEDs (Figures 5 and 6). The LEDs reduce the energy requirements of algae oil production as they consume 50% of the energy of the fluorescent lights. The oil content of the algae for all six cases was presented in Figure 7. The oil would be used to produce biodiesel that would be blended with jet fuel to produce bio-jet fuel. The calculated light capture and carbon capture efficiencies (Figures 8 and 9) show that waste water and R.O. water efficiencies are comparable to other literature values. The effect of light intensity on the algae productivity (Figures 10 and 11) show the increase in algae growth and lipid production in both R.O. and waste water. The present work demonstrates that Chlorella Vulgaris growth in municipal waste water using red-blue or red LEDs have potential for larger scale bio-jet production while reducing energy and fresh water requirements.

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