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Effect of temperature and light on the growth of algae species: A review

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ABSTRACT

Algae are fast growing biomass and can be converted to Biodiesel fuel. The demand of biodiesel is growing worldwide. Microalgae need a light:dark regime for productive photosynthesis. Light conditions and Temperature affect directly the growth rate of microalgae (duration and intensity).Literature review of some Green algae species *Chlorella, Spirogyra, Chlamydomonas, Botryococcus, Scenedesmus, Neochloris, Haematococcus, Nannochloropsis, Ulva* species and few species of brown algae, red algae, blue green algae were chosen to study the effect of temperature and light intensity on their growth. Optimum temperature range 20 °C to30 °C was observed for growth of different algae species. Light irradiance varies between 33 μmol m^{-2} s^{-1} to 400 μmol m^{-2} s^{-1}. Maximum growth rate was found 1.73 d^{-1} for *Selenastrum minutum* at 35 °C and 420 μmol m^{-2} s^{-1} irradiance. Minimum growth rate (0.10 d^{-1}) was reported for *Botryococcus braunii* KMITL 2 strain at temperature 25 °C, photoperiod 24:0 and 200 μmol m^{-2} s^{-1} irradiance.

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1. Introduction

Energy is the basic factor for human to sustain economic growth. After Industrial sector, transportation sector is the second largest energy consuming sector. Fossil fuel energy consumption in the transportation sector is from oil. Because fossil fuels are limited, so there is a need to use alternative sources of energy. Algae are most auspicious feedstock for biodiesel production, due to the presence of lipid and fatty acids present in their cell membrane. Algae are primitive unicellular or multicellular photosynthetic organism. Algae contain chlorophyll and other pigments for photosynthesis, which trap light energy from the Sun. During photosynthesis light energy is converted into chemical energy. Algae stored energy in the form of starch and carbohydrate (complex sugars). Algae can be found in freshwater, saltwater, marine water and on the surfaces of moist soil or rocks. There are seven groups of algae. They are grouped according to the types of pigments they use for photosynthesis, the makeup of their cell walls, the types of carbohydrate compounds they store for energy. There are many types of algae like green algae, red algae, brown algae and red–green algae (cyanobacteria) etc. Algal growth occurs in mostly damp and moist places. Several parameters affected the algal growth but role of light is very important. The growth of all algal species was found highly dependent on solar radiation of the pond or water body. The number of investigators was studied and reported the influence of different quality and quantity, natural and artificial light in addition to temperature difference. Light, darkness, light limitation, light quality, photoperiod, temperature, irradiance and seasons are important factor for algal growth, reproduction as well as lipid accumulation in algae. Investigator examined the light fluctuation affected phytoplankton community structure and diversity. Seasonal change in day length caused the growth of phytoplankton. Resource fluctuations can have an important role in structuring ecological communities [1]. Biofuels from algal cultivation is currently a great prospective. Light is an important factor to control the biomass and lipid production in algae. Algal growth rates increased with increasing temperature up to a certain limit. Various investigators observed that incident light is an important growth factor in the form of photon flux density [2]. Algal growth is affected by different types of shading light. Algae growth is inhibited by shedding light. After removing shading light materials, algae can resume growing rapidly. Chlorophyll-*a* content, algae cell density, pH and DO can grow rapidly [3]. Light is a fundamental variable for benthic algae. Vital role of light is assimilation of carbon dioxide. The work carried out by different investigator & researchers was summarized to select the proper light levels and temperature for the better growth of different species of algae and produce more biodiesel. This review paper is focused on the effect of light, temperature, irradiance and photoperiod on the growth of algae.

2. Effect of light on the growth of different algae species

Algae are a ubiquitous photosynthetic organism. Various external and internal factors affected the algal growth. Light is an essential source for autotrophic growth and photosynthetic activity. Algae contained chlorophyll *a* and *b*, which is major light harvesting pigments are sensitive to blue and red light. Studies have shown that green algae grow better in blue and red light because they contain chlorophyll *a* and *b* which are major light harvesting pigments and sensitive to these wavelengths. Temperature strongly influences the cellular chemical composition, uptake of nutrients, CO_2 and the growth rates for every species of algae. Light intensity, light–dark cycle as well as environmental factors also play significant role in algal growth, biomass accumulation and biodiesel production.

2.1. Green algae

2.1.1. Chlorella species

Chlorella species are single cell green algae. It contains photosynthetic pigment chlorophyll *a* and chlorophyll *b*. In the presence of water,

sunlight, CO_2 and nutrients *Chlorella* cells divided faster. Temperature and light required the autotrophic growth of *Chlorella minutissima* was observed. The light source was provided by a 400-W Phyto-Claude halogen lamp. *C. minutissima* was grown at temperatures between 10 °C and 35 °C and under irradiances from 30 μmol m^{-2} s^{-1} to 550 μmol m^{-2} s^{-1} under light:dark cycle. Investigator observed the *C. minutissima* required minimum irradiance to sustain net growth. Maximum specific growth rate increased from 0.12 d^{-1} at 10 °C, to 0.66 d^{-1} at 30 °C. Specific growth rate of *C. minutissima* decreased from 35 °C [4]. Another investigator observed Optimum daytime temperature was 30 °C of *Chlorella pyrenoidosa* for maximum biomass and lipid production [5]. Response of micro algal growth to various light intensities (i.e. 400, 800, 1200, 1600, 2000, and 2400 μmol m^{-2} s^{-1}) was observed under the wavelength of red light. Light intensity 400 Effects of various LED light wavelengths and intensities on the performance of purifying synthetic domestic sewage by microalgae at different influent C/N ratios was too low to maintain the growth of microalgae *Chlorella vulgaris*, whereas 2400 μmol m^{-2} s^{-1} light intensity was too high to avoid photo inhibition [6]. Temperature, Irradiance and light are to be considered as an important factor for better algal productivity. Maintenance of temperature in open raceway pond is difficult. The optimum water temperature needed for cultivation of microalgae ranges from 15 to 30 °C beyond this temperature range micro algal cell damage or death may occur. Another investigator reported 25 °C to be the optimum temperature for growth of freshwater microalgae belonging to genus *Chlorella* with a growth rate of 1.099 d^{-1} and cell concentration of 5.814 after 6 days. *Chlorella protothecoides* was cultivated heterotrophic method at 28 ± 1 °C temperature. The growth response of *Chlorella sorokiniana* at certain irradiance, Dissolve Oxygen and temperature was observed. The growth (biomass productivity) and chlorophyll fluorescence were reduced when the dissolved oxygen and temperature were elevated [7]. *C. vulgaris* UTEX 259 cultured in flasks of 0.25 dm^3 with 0.1 dm^3 of nutrient media, temperature 27 °C on a shaker rotated at 150 rpm. Bubbled air was passed into the shaking flask for sufficient aeration. Continuous illumination was supplied at an average light intensity of 200 ± 50 μmol m^{-2} s^{-1} with twelve 20 W warm white fluorescent tubes (Korea General Electric, Korea). The cells were sub cultured everyday by replacing 50% of the culture broth with fresh medium. The concentration of *C. vulgaris* UTEX 259 before replacing the medium was maintained around 1.8 kg dry weight m^{-3}. The corresponding doubling time was therefore estimated to be approximately 33 h [8]. *Chlorella fusca* and *Chlorella saccharophila* were grown under high (20 W m^{-2}) and low (5 W m^{-2}) intensities of white light. It was observed that compensation point of photosynthetic capacity and light intensity of these three strains was high. There was no significant change in the pigment composition or distribution of pigment protein complexes [9]. *Chlorella* can grow normally in 5 °C to 30 °C. The optimum temperature is 25 °C. *C. pyrenoidosa* cultivated in a defined media and set temperature was at 5, 10, 15, 20, 25, 30 and 35 °C respectively. Illumination intensity was 8000 lx. Concentration, dissolved oxygen and protein content of *C. pyrenoidosa* was measured every 2.5 h. It was observed 20–25 °C temperature was suitable for the growth of *C. pyrenoidosa.* The maximum increment of content of chlorophyll is up to 0.080 μg ml^{-1} at 25 °C [10]. Chlorella grown at 27 °C had a doubling time of 8.6 ± 0.6 h with the compared with 48.5 ± 2.6 h for cells grown at 5 °C. Low temperature may reduce rates of photosynthesis. The effect of irradiance at low growth temperature, cells were grown at 5 °C and μmol m^{-2} s^{-1} [11]. The heat and light resistant *Chlorella* species R-06/2, isolated from a geothermal well at 42 °C. *Chlorella* species R-06/2 had a high photosynthetic productivity over a broad temperature range 26–39 °C. *Chlorella* species R-06/2 grow at 44 °C to 51 °C temperature and light influence (16 klx) up to 4 h [12]. *C. vulgaris* when exposed to 42 °C for 15 min decreased autospore mother cell formation. *Pithophora oedogonia* and *Cladophora glomerata* better survived at diurnal temperature range of 10–28 °C. Growth temperature of *Vaucheria geminata* was 14–26 °C [13].

2.1.2. Enteromorpha species

The light intensity significantly affected spore biomass of *Enteromorpha* species, spore biomass increased with increasing amount of available light. Maximum photon flux density (PFD), 90 μE m^{-2} s^{-1} allowed a significantly higher algal recruitment when compared with the other two tested PFD's (20 μmol m^{-2} s^{-1} and 40 μmol m^{-2} s^{-1}). Salinity also had a significant effect on spore biomass. Spore biomass were strongly limited at 5 psu, favored at 20 psu and highly increased at 35 psu [14].

2.1.3. Spirogyra species

Influence of different environmental factors: light intensity, light quality, photoperiod, temperature, radiations, season, nutrients (inorganic, organic), biotic factors, osmotic stress, pH on algal growth and reproduction. *Spirogyra* species grow from February to April, when water temperature ranged from 10 °C to 17 °C (12:12 h light–dark period). Conjugation occurs in 2 days when it was moved to the laboratory and kept in Bold's basal medium at 20 °C, photoperiod 16:8 h L:D at > 20 μmol m^{-2} s^{-1}).

2.1.4. Chlamydomonas species

Growth characteristics have been shown to have a significant impact on the fatty acid profiles of *Chlamydomonas* species when cultivated at 20 °C [15]. The rate of irreversible damage was accelerated by increasing the photon Flux density (50 μmol m^{-2} s^{-1} to 1500 μmol m^{-2} s^{-1}) for cultivation of *Chlamydobotrys stellata* and (150 μmol m^{-2} s^{-1} to 5000 μmol m^{-2} s^{-1}) for *Chlamydomonas reinhardtii* [16]. To find out the electric light source for algae production, Growth of the green microalgae *C. reinhardtii* was observed under red and blue lasers. A white cold cathode lamp with spectral output similar to that of white fluorescent lamp served as control. The laser treatments tested included: 655-nm Red; 680-nm Red; 655-nm Red + 474-nm Blue and 680-nm Red + 474-nm Blue. *C. reinhardtii* was grown and divided under the 655 and 680 nm red lasers as well as under the white-light control [17]. Genetically engineered light harvesting antennae of *C. reinhardtii* with the use of genetic transformation of chloroplast or nuclear genome develop higher resistance to photo damage and increased light penetration in liquid culture. Genetically modified *C. reinhardtii* showed more efficient conversion of solar energy to biomass [18]. Growth rate and the cell density of *C. reinhardtii* cc124 observed under four different light regimes: continuous illumination (light period), continuous illumination with CO_2 bubbling (light + CO_2), 12:12 light:dark cycles, no illumination (dark period) and different carbon dioxide concentration. *C. reinhardtii* cc124 strain was grown under tris-acetate phosphate (TAP) medium. Initial pH was 6.8 and temperature 25 °C maintained under Solar Biofuels Consortium stirred-tank Photo bioreactor. Cultures grow under 12:12 light:dark cycles have a lower growth rate was 0.142 h^{-1}. Photoperiod 12:12 reduced30% (approximately) algal growth rate and cell density [19]. *C. reinhardtii* successfully grow under the 655 and 680-nm red lasers and under the white-light control.

2.1.5. Botryococcus species

Four strains of *Botryococcus species* (TRG, KB, SK, and PSU) were isolated from lakes and freshwater ponds in southern Thailand. Investigator observed in the presence of nitrogen rich condition, *Botryococcus strains* (TRG, KB, SK, and PSU) achieved a lipid content of 25.8%, 17.8%, 15.8% and 5.7%, respectively. In nitrogen deficient condition, high light intensity (82.5 μmol m^{-2} s^{-1}) and high level of iron (0.74 mM) lipid accumulation increased in TRG, KB, SK, and PSU strains up to 35.9%, 30.2%, 28.4% and 14.7%, respectively. In decreasing order the specific growth rate of *Botryococcus strain* KB, TRG, SK and PSU was 0.223 d^{-1}, 0.182 d^{-1}, 0.135 d^{-1} and 0.061 d^{-1} observed. *Botryococcus strain* TRG showed the highest lipid content of 25.8% and highest lipid productivity of 46.9 mg l^{-1} d^{-1} in nitrogen-rich medium. *Botryococcus*

strain KB has highest specific growth rate but lipid productivity was very low 39.7 d^{-1} due to lower lipid content (17.8%) [20]. Light increases both nitrate and nitrite assimilation rates in algae up to twenty-three times in dark condition [21]. *Botryococcus braunii* has been high lipid content. Optimal growth temperature 25–30 °C observed for the cultivation of *B. braunii*. Maximum growth temperature is 32 °C. *B. braunii* KMITL2 was isolated from a freshwater reservoir in central Thailand. The effects of light, nitrogen, phosphorus, iron cultivation time and salinity on lipid production were studied by varying parameters at a time. *B. braunii* KMITL2 was cultured in *Chlorella* medium containing 222 mg l^{-1} phosphorus under continuous illumination of 200 μmol m^{-2} s^{-1} with salinity of 0 psu, maximum lipid content 54.69 ± 3.13% obtained. High lipid content of *B. braunii* KMITL 2 makes potential source for biodiesel production in tropical regions. The highest lipid content of *B. braunii* KMITL 2 was 0.45 g l^{-1} was obtained at light irradiance 538 μmol m^{-2} s^{-1}. Biomass of *B. braunii* KMITL 2 was 1.91 ± 0.24 g l^{-1} under the 24:0 light:dark cycle which was four times the biomass under 12:12 light:dark cycles [22]. Cultures exposed to low light intensity (87.5 μmol m^{-2} s^{-1}) showed a higher biomass compared to others (200 and 538 μmol m^{-2} s^{-1}). The difference in growth was possibly due to efficient in utilizing low irradiances for inorganic assimilation. High light intensities of 200 and 538 μmol m^{-2} s^{-1} limited algal growth, but gave the benefit of higher lipid content and yield. Investigator examined the Specific growth rates of *B. braunii* strain Showa under a wide range of CO_2, salinity, temperature, and irradiance conditions. CO_2 concentration of 0.2–5% and no addition of salinity were favorable conditions for growth. *B. braunii* strain Showa observed at temperatures 5, 15, 20, 25, 27, 30, 35, 38 and 45 °C; maximum specific growth rate yield d^{-1} was 0, 0.095, 0.207, 0.392, 0.431, 0.496, 0, 0 and 0 respectively. Growth rate become stable at 15–30 °C. *B. braunii* strain Showa cannot grow at 5 °C and above 35 °C under any irradiance levels. Maximum specific growth rate of *B. braunii* strain Showa was 0.5 d^{-1} doubling time of 1.4 days observed at 30 °C and 850 μmol m^{-2} s^{-1} [23].

2.1.6. Scenedesmus species

Scenedesmus armatus was studied under the 14:10 light:dark period. Photosynthetic rate and photosynthetic efficiency of the cells were calculated. Oxygen evolution gradually increased from the beginning of the cell cycle reaching its maximum at 12 h and then slowly declined towards the end of the cell cycle [24]. At low light intensity, *Scenedesmus* species duplicate their pigment apparatus. Photosynthetic apparatus adapted within 6–8 h to the new condition.

Scenedesmus sp. LX1 could grow in a wide range of temperature (10–30 °C). The growth activation energy (E_a) was observed 49.3 kJ mol^{-1}. The optimal temperature to produce microalgae biomass and lipid was 20 °C, and after 15 days of batch cultivation biomass productivity, lipid productivity and Tri-acyl glycerol were 313.3, 112 and 14.7 $(gP)^{-1}$ obtained respectively. The content of polyunsaturated fatty acids decreased with the increase of cultivation temperature [25]. Combined technology for advanced wastewater treatment and microalgae biomass production is reported. *Scenedesmus* sp. LX1 was cultured in a batch type bioreactor. The average specific growth rate of *Scenedesmus* sp. LX1 was approximate 0.09 d^{-1}.However under continuous operation with an inflow of 60 l h^{-1}, the average specific growth rate was only 0.02 d^{-1}. During the experiment light intensity was 3000 lx and temperature was 22–28 °C. The maximum light intensity on the column face was about 6000 lx [26]. *Scenedesmus obliquus* CNW-N was grown in modified Detmer's Medium (DM), under a light intensity of 60–540 μmol m^{-2} s^{-1} (illuminated by TL5 lamp). The light intensity was measured by a Li-250 Light Meter with a Li-190SA pyranometer sensor. Light intensity promotes cell growth, carbohydrate, lipid productivity, and CO2 fixation efficiency in *S. obliquus* CNW-N was observed. The specific growth rate increased dramatically with rising light intensity up to a certain limit. After saturation condition growth rate decreases. The highest value of specific growth rate was around 1.65–1.8 d^{-1} in the light saturation region (180–540 μmol m^{-2} s^{-1}) the biomass productivity and the CO_2 fixation rate was increased significantly along with the rising light intensity, until they reached the highest value. More than 540 μmol m^{-2} s^{-1} irradiance drops in both CO_2 fixation rate and biomass productivity. Excessive illumination would inhibit the biomass production and the CO_2 fixation ability, which is commonly recognized as the photo-inhibition effect. The maximum biomass productivity of 840.56 d^{-1} was observed at a light intensity of 420 μmol m^{-2} s^{-1}, with the highest CO_2 fixation rate 1435.90 mg l^{-1} d^{-1} [27] (Tables 1 and 2).

2.1.7. Skeletonema costatum

Growth of a diatom *Skeletonema costatum* with different monochromatic light was observed. Under different monochromatic light, saturated light intensity decreases and the growth rate increases with the increasing of spectrum absorption coefficient. The growth rate of *S. costatum* increased with the increasing light intensity from 20 to 40 μmol m^{-2} s^{-1}. The highest growth rate of *S. costatum* is 0.3006 d^{-1} at 50 μmol m^{-2} s^{-1} [28]. The growth rate of algae is highly dependent upon rate of photosynthesis. Algal photosynthetic efficiency is decided at a certain pH, temperature, light intensity and the duration of illumination and nutrition conditions [29]. Ultraviolet irradiance adversely affected algal growth, Photosynthesis, photo reduction and Hill reaction. Shape of algal chloroplast was changed at 520 nm light–dark absorbance. The endogenous plastoquinone level dropped about 40% but not only due to UV-has radiation [30]. Ultraviolet irradiation inhibited photosynthesis [31].

2.1.8. Chaetomorpha valida

The effect of temperature and irradiance on growth and reproduction of *Chaetomorpha valida* was investigated. Healthy growth and reproduction occurred in the range of 17–29 °C while upper lethal limit was at 33 °C. A suitable temperature range was 21–29 °C. High irradiance level 108 μmol m^{-2} s^{-1} were more favorable for growth and reproduction [32].

2.1.9. Neochloris oleoabundans

Neochloris oleoabundans UTEX 1185 grow in *f*/2 medium under fluorescent light (40 μmol m^{-2} s^{-1}) at 25 °C, 2% CO_2 and 120 rpm orbital shaking. The average value for the different experiments at high light intensity was about 500 μmol m^{-2} s^{-1}, while at low light intensity the average incident photon flux density was about 200 μmol m^{-2} s^{-1}. Saturated condition of *N. oleoabundans* UTEX

Table 1
Biomass concentration and biomass productivity obtained from *Scenedesmusobliquus* strain at 28 °C temperature and 140 μmol m^{-2} s^{-1} irradiance [27].

S. no.	Strain	Biomass conc. (g l^{-1})	Biomass productivity (mg l^{-1} day^{-1})	Lipid content (%)
1.	*S. obliquus* AS-6-1	1.56 ± 0.18	378.9 ± 40.4	11.71
2.	*S. obliquus* CNW-N	2.10 ± 0.08	440.68 ± 15.79	10.32
3.	*S. obliquus* CNW-1	1.44 ± 0.20	394.2 ± 42.2	9.17
4.	*S. obliquus* FSP-3	1.64 ± 0.12	351.2 ± 20. 8	10.48
5.	*S. obliquus* ESP-5	1.91 ± 0.09	375.1 ± 18.9	8.32
6.	*S. obliquus* ESP-7	1.34 ± 0.12	217.6 ± 20.0	9.74

Table 2
Growth rate and Specific growth rate of different algae species at various temperatures, light:dark period & light intensity/ irradiance.

S. no.	Algal species	Temp (°C)	L:D period	Nutrient/media	Irradiance ($\mu mol\ m^{-2}\ s^{-1}$)	Salinity (psu)	Lipid Content (%)	Growth rate (d^{-1})	specific growth rate (d^{-1})	Ref.
1.	*Enteromorpha sp.*	20	14:10	Seawater	90	5	N/A	*0.273	N/A	[14]
2.	*Enteromorpha sp.*	20	14:10	Seawater	40	5	N/A	*0.180	N/A	[14]
3.	*Enteromorpha sp.*	20	14:10	Seawater	20	5	N/A	*0.134	N/A	[14]
4.	*Enteromorpha sp.*	20	14:10	Seawater	90	20	N/A	*0.355	N/A	[14]
5.	*Enteromorpha sp.*	20	14:10	Seawater	40	20	N/A	*0.245	N/A	[14]
6.	*Enteromorpha sp.*	20	14:10	Seawater	20	20	N/A	*0.203	N/A	[14]
7.	*Enteromorpha sp.*	20	14:10	Seawater	90	35	N/A	*0.387	N/A	[14]
8.	*Enteromorpha sp.*	20	14:10	Seawater	40	35	N/A	*0.341	N/A	[14]
9.	*Enteromorpha sp.*	20	14:10	Seawater	20	35	N/A	*0.348	N/A	[14]
10.	*Botryococcusstrain* SK	25 ± 1	16:8	Modified CHU 13 (N-rich)	33	N/A	15.8	N/A	0.135	[20]
11.	*Botryococcus strain* SK	25 ± 1	16:8	Modified CHU 13 (N-deficient)	33	N/A	20.7	N/A	N/A	[20]
12.	*Botryococcus strain* TRG	25 ± 1	16:8	Modified CHU 13 (N-rich)	33	N/A	25.8	N/A	0.182	[20]
13.	*Botryococcus strain* TRG	25 ± 1	16:8	Modified CHU 13 (N-deficient)	33	N/A	32.3	N/A	N/A	[20]
14.	*Botryococcus strain PSU*	25 ± 1	16:8	Modified CHU 13 (N-rich)	33	N/A	5.7	N/A	0.061	[20]
15.	*Botryococcus strain PSU*	25 ± 1	16:8	Modified CHU 13(N-deficient)	33	N/A	24.3	N/A	N/A	[20]
16.	*Botryococcus strain KB*	25 ± 1	16:8	Modified CHU 13 (N-rich)	33	N/A	17.8	N/A	0.223	[20]
17.	*Botryococcus strain KB*	25 ± 1	16:8	Modified CHU 13 (N-deficient)	33	N/A	23.9	N/A	N/A	[20]
18.	*B. braunii IPE 001 B*	25	12:12	Modified CHU 13	35	N/A	N/A	N/A	0.15	[23]
19.	*B. braunii Yayoi B*	25	12:12	Modified CHU 13	240	N/A	N/A	N/A	0.20	[23]
20.	*B. braunii 765*	25	24:0	Modified CHU 13	150	N/A	N/A	N/A	0.13	[23]
21.	*B. braunii KMITL 2*	25	24:0	Modified CHU 13	200	N/A	N/A	N/A	0.10	[23]
22.	*B. braunii UC 58*	25	24:0	Modified CHU 13	250	N/A	N/A	N/A	0. 42	[23]
23.	*B. braunii*	25	N/A	Modified CHU 13	850	N/A	N/A	N/A	0.5	[23]
24.	*N. oleoabundans UTEX 1185*	25	N/A	BBM	200 (high light)+N_2 rich	N/A	N/A	N/A	1.74 ± 0.03	[35]
25.	*N. oleoabundans UTEX 1185*	25	N/A	BBM	70 (Low light)+N_2 replete	N/A	N/A	N/A	0.75	[35]
26.	*N. oleoabundans UTEX 1185*	25	N/A	BBM	200 (high light)+N_2 replete	N/A	N/A	N/A	1.29	[35]
27.	*N. oleoabundans UTEX 1185*	25	N/A	BBM	70 (Low light)+N_2 rich	N/A	N/A	N/A	1.15 ± 0.10	[35]
28.	*H. pluvialis UTEX 2505*	27	N/A	Modified BBM	260	N/A	N/A	N/A	N/A	[39]
29.	*P. pectinatus*	10–37	N/A	N/A	6–120	N/A	N/A	(+) growth	N/A	[43]
30.	*P. donghaiense*	27	N/A		N/A	N/A	N/A	N/A	0.77	[48]
31.	*C. ovata CO2*	30	N/A	modified SWM-3	N/A	25	N/A	1.21	N/A	[60]
32.	*C. ovata CO3*	25	N/A	modified SWM-3	N/A	25	N/A	1.11	N/A	[60]
33.	*C. ovata CO8*	30	N/A	modified SWM-3	N/A	30	N/A	1.47	N/A	[60]
34.	*C. marina*	25	12:12	Sea water	400	28	N/A	1.08	N/A	[61]
35.	*C. marina*	25	12:12	Sea water	150	30	N/A	> 0.5	N/A	[61]
36.	*C. marina*	10–30	12:12	Sea water	150	15–45	N/A	> 0.3	N/A	[61]
37.	*N. thermalis*	22 ± 1 [WL]	N/A	F" Medium	150	34 ± 1	N/A	0.30 ± 0.05	N/A	[70]
38.	*N. thermalis*	22 ± 1 [BL]	N/A	F" Medium	150	34 ± 1	N/A	0.35 ± 0.05	N/A	[70]
39.	*N. incerta*	22 ± 1 [WL]	N/A	F" Medium	150	34 ± 1	N/A	0.13 ± 0.02	N/A	[70]
40.	*N. incerta*	22 ± 1 [BL]	N/A	F" Medium	150	34 ± 1	N/A	0.11 ± 0.02	N/A	[70]
41.	*P. reticulatum*	15	12:12	f/2 medium	70–90	25 and 30	N/A	Highest growth	N/A	[78]
42.	*S. minutum*	30	15:9	Mineral medium	365	N/A	N/A	N/A	1.55	[97]
44.	*C. microporum*	30	15:9	Mineral medium	390	N/A	N/A	N/A	1.59	[97]
45.	*C. subprotumidum*	30	15:9	Mineral medium	360	N/A	N/A	N/A	0.88	[97]
46.	*P. globosa*	18 ± 2	12:12	Seawater	150	30	N/A	1.17	N/A	[99]
47.	*T. rotula*	18 ± 2	12:12	Seawater	150	30	N/A	0.60	N/A	[99]
48.	*P. Donghaiense*	18 ± 2	12:12	Seawater	70	30	N/A	0.36	N/A	[99]

*=Mean growth rate, psu=salinity, WL=white light, BL=blue light.
Max growth=on the basis of chlorophyll conc., BBM=Bold Basal Medium.

1185 at 230 $\mu mol\ m^{-2}\ s^{-1}$ was observed. First day biomass concentration was reported 0.42 ± 0.05 d^{-1} on the basis of dry weight (DW). High oxygen concentrations negatively affected the growth rate of *N. oleoabundans* UTEX 1185 at high light conditions. The highest growth rate was 1.36 d^{-1} reported at 500 $\mu mol\ m^{-2}\ s^{-1}$ saturated light intensity [33]. Excess light absorption and growth limiting nitrogen supply rates were combined, which resulted in accumulation of TAGs (from 1.5% to 12.4% w/w) in visible lipid

bodies in *N. oleoabundans*, while cell replication was sustained. *N. oleoabundans* UTEX 1185 was cultivated in 250 ml shake flasks. The shake flaks contained 100 ml filter sterilized (pore size 0.2 μm), defined medium at a pH of 7.5. This medium was designed in such a way, that 4 g l^{-1} nutrient replete biomass could be sustained [34]. *N. oleoabundans* is the best source for biodiesel production. To evaluate the effect of three different light intensities (50, 94 and 136 μmol m^{-2} s^{-1}), on the cell density and cell size of *N. oleoabundans* cultivated in a modified Bold's Basal medium (BBM) was observed. It was found that cell density was highest at 136 μmol m^{-2} s^{-1} and cell productivity was sustained for 15 days. The average cell density obtained at highest light intensity was 4.1×10^5 cells ml^{-1}. The cell productivity at the end of day 1 in which a maximum specific growth rate was (1.30 d^{-1}) and 3.1×10^5 cells ml^{-1} d^{-1} obtained. Cell size was affected significantly by light intensity, being higher at the lowest (10.92 ± 1.26 μm) and medium (11.88 ± 1.12 μm) levels tested, compared to the size observed at the highest level (5.25 ± 1.26 μm) [35].

2.1.10. Haematococcus species

With the use of intermittent flashing light from blue light emitting diodes (LEDs), observed the effects of the incident light intensity (2–12 μmol m^{-2} s^{-1}), duty cycle (17–67%) and frequency (25–200 Hz) of flashing on the cell growth and astaxanthin production from the green alga *Haematococcus pluvialis*. Flashing light at an incident intensity of 8 μmol m^{-2} s^{-1} gave the same final astaxanthin concentration was obtained under continuous light illumination at 12 μmol m^{-2} s^{-1}, thus reducing energy Consumption by 1/3. We therefore conclude that flashing light from blue LEDs is a promising illumination method for indoor algal cultivation using photo bioreactors [36]. A model for the continuous production of green cells of *H. pluvialis* was discussed in both indoor and outdoor conditions. Indoor experiments were carried out in four-jacketed bubble column photo bioreactors, with different maximum irradiances of 1000, 1500, 2000 and 2500 μmol m^{-2} s^{-1}. Outdoor experiments were performed in an airlift type tubular photobioreactor at pilot scale temperature was maintained 20 °C and 12:12 period. The optimal dilution rate was 0.04 h^{-1}, and that higher external irradiance resulted in higher biomass productivity in all cases, with a maximum value of 0.58 g l^{-1} d^{-1}. Astaxanthin accumulation was not observed in spite of the high levels of irradiance, and cells remained in the flagellated-palmeloids green form whatever the culture conditions. High dilution rates produced small cells of 22 μm diameter, with a high nitrogen content of up to 10% dry wt. The average irradiance within the reactor was the main factor determining the behavior of the cultures, although the external irradiance impinging on the reactor surface also influenced the results, indicating the existence of photo inhibition. The influence of both external and average irradiance on the growth of *H. pluvialis* was modelized. The accuracy of the model obtained was verified on a 0.22 m^3 outdoor tubular photo bioreactor operated in both discontinuous and continuous mode, obtaining a maximum biomass productivity of 0.68 g l^{-1} d^{-1}. The model reproduced the experimental data of biomass concentration and productivity, cell size and nitrate consumption, providing to be a powerful tool for optimizing the design and operation of outdoor photo bioreactors for the production of *H. pluvialis*. Value of the steady-state biomass concentration ranged from 2.8–0.4 g l^{-1}. The dilution rate of maximized productivity was 0.04 h^{-1} (for 12:12 h of continuous operation), the highest value of biomass productivity was 0.58 g l^{-1} d^{-1}, under the highest tested external irradiance of 2500 μmol m^{-2} s^{-1}. The biomass productivity increased with the irradiance whatever the dilution rate was, obtaining maximum biomass productivities of 0.58 g l^{-1} d^{-1} at the optimal dilution rate of 0.04 h^{-1} [37]. *Haematococcus lacustris* UTEX 16 are cultivated in photobioreactor in modified Bold's basal medium (MBBM). Culture incubated at 25 °C under continuous Shaking (175 rpm) and irradiated at 40 μmol m^{-2} s^{-1} with fluorescent lamps. *H. lacustris* UTEX 16 cells were cultivated for 6 days under normal light irradiance of 40 μmol m^{-2} s^{-1}, then induced to accumulate astaxanthin by exposure to a continuous light irradiance of 200 μmol m^{-2} s^{-1} for 3 days further with fluorescent lamps as a light source [38]. Effect of temperature and irradiance on *H. pluvialis* UTEX 2505 has been studied. Investigator observed the perfect levels of temperature and irradiance have been reported to range from 14–28 °C and 30–200 μmol m^{-2} s^{-1}. Maximum growth rate for *H. pluvialis* UTEX 2505 was found at 27 °C and at 260 μmol m^{-2} s^{-1}. Maximal Chlorophyll-*a* concentration produced at 27 °C temperature and 35 μmol m^{-2} s^{-1} irradiance, while maximal Chlorophyll-*b* can be found at 28 °C and 33 μmol m^{-2} s^{-1} [39].

2.1.11. Nannochloropsis species

Growth of *Nannochloropsis* species was studied under different light wavelengths and intensities. Light wavelengths of primary monochromatic (red, green and blue LEDs) and in white LEDs. The sequence of maximum specific growth rate for LEDs was blue > white > green > red. *Nannochloropsis* species achieved a maximum specific growth rate of 0.64 d^{-1} and 0.66 d^{-1} in phototrophic and mixotrophic cultures under blue light respectively [40].

2.1.12. Pycnococcus provasolii

The growth, photosynthesis and respiration rates of *Pycnococcus provasolii* Guillard were measured with the reference of Irradiance, temperature and photoperiod. The algae showed positive photo adaptation to low irradiance and this is achieved mainly by increasing the size of the photosynthetic units. Chlorophyll-*b*: chlorophyll-*a* ratio increased with decreasing photon flux density was found. The algae further compensated for low light energy supply by reducing the rates of respiration. The values of the initial slope of the growth versus irradiance curve were higher than average (0.0016–0.0022 h^{-1} (μmol m^{-2} s^{-1})$^{-1}$ at 20 °C). 24:0 h light regime did not harmful to *P. provasolii* Guillard. However, light energy was utilized less efficiently under 24:0 than under 12:12 h Period [41].

2.1.13. Potamogeton pectinatus

Potamogeton pectinatus a water plant species grew at 10–37 °C under low irradiances (6–120 μmol m^{-1} s^{-1}). Growth of *P. pectinatus* was influenced by temperature and irradiance. Chlorophyll-*a* and chlorophyll-*b* pigment are influenced by temperature. At 37 °C no leaves were produced. Results indicated the optimum temperature for early growth of *P. pectinatus* is approximately 23–30 °C [42]. Investigators identify light induced photosynthetic characteristics of 14 freshwater algal species. It was observed that photo inhibition occurs due to low values (< 225 μmol m^{-2} s^{-1}) of the saturation parameter. Compensation irradiance (I_c) was less than 20 μmol m^{-2} s^{-1}. Some species (e.g. *Batrachospermum delicatulum*) can also tolerate high irradiances (up to 2400 μmol m^{-2} s^{-1}) [43].

2.1.14. Ulva species

Ulva species have been good reproductive ability. In this paper Investigator observed the effect of photon irradiance, photoperiod, and spectral qualities of light on growth and reproduction of *Ulva pertusa*. *U. pertusa* exposed to different photoperiods (8:16, 12:12 and 16:8 h L:D period and continuous light regimes) combined with different photon irradiances (10 and 100 μmol m^{-2} s^{-1}). The size of the thallus discs of *U. pertusa* was greatest at 10 μmol m^{-2} s^{-1}; saturation of reproduction occurred at 30 μmol m^{-2} s^{-1}. Minimum irradiance for the growth of *U. pertusa* was 5 μmol m^{-2} s^{-1} and 10 μmol m^{-2} s^{-1} for reproduction [44].

2.2. Blue green algae (Cyanobacteria)

2.2.1. Microcystis aeruginosa

The combined effects of temperature, light intensity, and nitrogen concentration on the growth and polysaccharide content of *Microcystis aeruginosa* was observed. *M. aeruginosa* placed in media with different nitrogen concentrations (0.26, 2.55 and 25.47 mg l^{-1}), temperatures (25 °C and 30 °C) and two light intensities were (35 and 80 μmol m^{-2} s^{-1}) for 12 days. Light intensity and nitrogen concentration independently had significant impact on soluble extracellular polysaccharide, bound polysaccharide and total polysaccharide content. Under low nitrogen concentrations growth of *M. aeruginosa* was significantly inhibited. High light intensity increased growth of *M. aeruginosa* [45]. Investigator observed the algal biomass reduced more than 65% in the presence of light shading and aeration at 5 day experiment. *Microcystis* species floated upwards during light deficiency [46].

2.2.2. Synechocystis species

Synechocystis species is a highly light tolerant strain and suitable for outdoor cultures. Maximum specific growth rate observed 0.108 h^{-1} at an Average Irradiance of 930 μmol m^{-2} s^{-1}. *Synechocystis* species was considered a good photosynthetic organism for CO_2 biofixation. Light utilization efficiency of *Synechocystis* species under a 16:8 photoperiod of 200 μmol m^{-2} s^{-1} at 25 °C [47]. Investigators observed the carotenoid and chlorophyll-*a* contents under two different growth irradiances in four freshwater cyanobacteria strains. The cyanobacteria species: *Anabaena cylindrica* ASW 01033, *Anabaenopsis elenkinii* ASW 01057, *Anabaena torulosa* ASW 01023 and *Nostoc* species ASW 042 was grown in batch cultures in a nutrient solution. The cultures were kept at 20 °C and 120 μmol m^{-2} s^{-1} (HI 1/4 high growth irradiance) and at 15 μmol m^{-2} s^{-1} (LI 1/4 low growth irradiance) respectively. Standard fluorescent tubes, Philips, TL M 40 W/84 RS was used. *A. torulosa* ASW 01023 achieved highest biomass with approximately 1900 mg Chl-*a* l^{-1} and 1000 mg total carotenoids l^{-1}. *Nostoc* species ASW 042 showed significantly increased amounts in the LI cultures, whereas differences of the remaining HI and LI cultures were not significant [48]. Investigator observed the growth rate of *Synechococcus* WH7803 was 1.4 d^{-1} at irradiances from 200 to 2000 μmol m^{-2} s^{-1} under continuous light in nutrient replete media without photoinhibition. Concentration of photosynthetic pigments like phycoerythrin, phycocyanin, and chlorophyll-*a* were inversely related to growth irradiance. Phycoerythrin shows highly adaptation. Concentrations of phycoerythrin 20 times vary within the cell 30 μmol m^{-2} s^{-1} to 700 μmol m^{-2} s^{-1} [49]. *Synechocystis*has been grown under irradiances (PAR) ranging from 16–1450 μmol m^{-2} s^{-1}, and differing spectral compositions (white, blue and green). Investigator observed, due to drastic changes in chlorophyll and phycocyanin content $cell^{-1}$ undergo extreme variations [50].

2.3. Red algae

2.3.1. Tichocarpus crinitus

Storage and structural lipid were affected by the light intensity. *Tichocarpus crinitus* exposed to different levels of photon irradiance: 70–80% and 8–10% of the incident photosynthetic active radiation (PAR). Fatty acid composition of lipid in *T. crinitus* was not affected under different light conditions. However unsaturated acid 20:5n-3 was slightly increased in *T. crinitus* under 8–10% PAR compared to 70–80% PAR. Light conditions influenced on total lipid content, 4.2 ± 0.5 and 3.4 ± 0.3 mg g^{-1} fresh weights in algae exposed to 8–10% PAR and 70–80% PAR respectively [51].

2.3.2. Skeletonema costatum

Effects of light intensity and three LED monochromatic lights (blue, green, and red) on the growth of *S. costatum*, a marine species are investigated in batch culture conditions. Seven light intensities (20, 30, 40, 45, 50, 60 and 80 μmol m^{-2} s^{-1}) are used to evaluate the specific growth rate. The growth rate of *S. costatum* under blue light is higher within saturated light intensity to the compared with red and green light. Saturated light intensity of LED monochromatic light is lower under blue light and higher under green light. Under different monochromatic light, the saturated light intensity decreases and the growth rate increases with the increasing of spectrum absorption coefficient [52].

2.3.3. Heterosigma species

Heterosigma akashiwo is a golden brown marine alga. Investigator observed the effect of temperature and light on the germination of *H. akashiwo* cysts. The suspension samples were incubated at temperature: 5, 8, 12, 16, 20, 25 and 30 °C at 80 μmol m^{-2} s^{-1} for 12 d^{-1}. The maximum number of 12 motile cells that emerged per day on day 5 at 12 °C; 40 motile cells on day 3 at 16 °C; 45 motile cells on day 2 at 20 °C; 63 motile cells on day 2 at 25 °C; and 43 motile cells on day 2 at 30 °C at the higher temperatures the cell numbers gradually decreased. Temperature ≥ 16 °C with light was the favorable conditions for survival of the cyst [53].

2.3.4. Chondrus yendoi

After the macro algae exposed to the low light stress for 10 days, Investigator observed a significant negative effect on the growth of *Chondrus yendoi*. Growth of *C. yendoi* was ceased at light intensities around 4% (~80 μmol m^{-2} s^{-1}) in July and 5.5% (~110 μmol m^{-2} s^{-1}) in August. Some individuals still grew at 1% (~20 μmol s^{-1} m^{-2}) of the natural light intensity, but others already showed necrosis under 34% (~692 μmol m^{-2} s^{-1}) and10% (~200 μmol m^{-2} s^{-1}) of the natural Irradiance [54].

2.3.5. Porphyra species

Maximum growth rates of *Porphyra dioica* were up to 33% d^{-1}, achieved with 0.1 g fw l^{-1} at 150 and 250 μmol m^{-2} s^{-1}. Growth rates of *P. dioica* were significantly affected by temperature and photoperiod. The highest growth rate 27.5% fw d^{-1} was recorded at 15 °C and 16:8, L:D period [55]. Sun and shade species of *Porphyra* were studied under short-term irradiance. Investigator observed higher radiation exposure (840 μmol m^{-2} s^{-1}) did not alter the Chlorophyll *a* concentration; however, a lower irradiance (40 μmol m^{-2} s^{-1}) for 48 h significantly increased the chlorophyll concentration [56]. Algae under light:dark cycles of 12:12 exhibited photosynthesis with more than two times higher levels in the light phase [57]. Algal growth is also affected by the quality of light. The effect of different light qualities (white, blue, green, yellow and red light) on photosynthesis measured as chlorophyll fluorescence, and the accumulation of photosynthetic pigments, proteins and the UV-absorbing mycosporine-like amino acids (MAAs) of red alga *Porphyra leucosticte*. Blue and white light promoted the highest accumulation of nitrogen metabolism derived compounds. In contrast, the lowest photosynthetic capacity, lowest electron transport rate, lowest photosynthetic efficiency and the growth rate were found under blue light, while higher values were found in red and white lights [58].

2.3.6. Chattonella species

Germination of the cysts of *Chattonella ovate* was observed at temperatures from 17.5 to 30 °C, but not at 15 °C or below. The optimum temperature for germination was 30 °C. Cysts of *Chattonella antiqua* and *Chattonella marina* germinated at temperatures from 15 to 30 °C, optimum temperature of germination was 22.5 °C. The lower

limit and optimum temperatures for germination of *Chattonella ovata* cysts was higher than for *C. antiqua* and *C. marina* [59]. Growth of *C. ovata*observed with 42 different combinations of temperature (10–30 °C) and salinity (10–35 psu), and under various light intensities (0–381 μmol m^{-2} s^{-1}). The three strains of *C. ovate* CO2, CO3, and CO8, tolerated a wide range of temperature (15–32.5 °C) and salinity (10–35 psu). High growth obtained at 20 °C and salinity of 20, and maximal growth rates of 1.21, 1.11 and 1.47 d^{-1} were found in the combination 30 °C and salinity of 25 psu for CO_2, 25 °C and 25 psu for CO3, and 30 °C and 30 psu for CO_2, respectively. The growth rate of *C. ovata* strains was higher than *C. antiqua* and *C. marina*. Growth of the *C. ovata* strain CO2 and CO8 was observed at the irradiance 15–45 μmol m^{-2} s^{-1} or more and was saturated at over 300 μmol m^{-2} s^{-1}. *C. ovata* prefers high temperature and salinity [60]. Few algal species tolerate a wide range of temperature and salinity. *C. marina* cultured under laboratory condition, optimal growth was >0.5/day obtained at 150 μmol m^{-2} s^{-1} irradiance, 25 °C temperature and 30 psu salinity. Same species when grown at 10 and 30 °C temperature and 15–45 psu salinity obtained good growth (>0.3/day). Faster growth rate achieved at 450 μmol m^{-2} s^{-1} irradiance. The negative growth rate of *C. marina* obtained at 10 μmol m^{-2} s^{-1}, growth rate was reduced at 800 μmol m^{-2} s^{-1}. Zero growth observed at 25 μmol m^{-2} s^{-1} irradiance. The maximum growth rate of *C. marina* (N-188) obtained at 200 μmol m^{-2} s^{-1} [61]. The growth rate of algae increased with increasing temperature up to a certain limit then saturation point starts and growth rate of algae start to decrease. Due to the Photo inhibition algal growth decreases after a certain light intensity and temperature. Photo inhibition is a phenomenon of decrease in photosynthesis rate, when plants are exposed to high irradiance. It is basically reduces the photosynthetic capacity [62]. Impact of short and long-term shifts from low to high light intensity (30–600 μmol m^{-2} s^{-1}) was observed on *Chattonella subsalsa* and dinoflagellate, *Prorocentrum minimum. P. minimum* had a significantly higher growth rate for the comparison of *C. subsalsa* when acclimated to the low or high light. However, the growth of *C. subsalsa* was significantly faster than *P. minimum* in the first 5 days prior a shift from low to high light. Growth rates were equivalent when both species were inoculated into the same flasks and shifted from low to high light. Maximum cell specific growth rate (d^{-1}) for *C. subsalsa* and *P. minimum* obtained at 600 μmol m^{-2} s^{-1} or for 5 days a shift from the low to high light was reported 0.504 ± 0.011 and 0.694 ± 0.023 d^{-1} respectively [63].

2.3.7. Porphyridium cruentum

Blue and red light used to improve the photosynthetic efficiency as well as extracellular polysaccharide in red alga *Porphyridium cruentum*. Maximum growth rate and extracellular polysaccharide production was 0.38 d^{-1} and 0.95 g l^{-1} respectively at 70 μmol m^{-2} s^{-1}, Photon flux density [64]. Investigator identified Optimum Photon flux density for growth and extracellular polysaccharide production of *P. cruentum* was 75 μmol m^{-2} s^{-1} [65].

2.3.8. Corallina elongate

Synthesis of Chlorophyll *a*, phycocyanin and allophycocyanin induced in *Corallina elongate* in the presence of red light. Investigator observed the phycoerythrin synthesis is not induced by red light [66].

2.3.9. Gracilaria species

The diverse growth conditions of photon flux density and temperature caused some differences in the distribution of the fatty acids in each species. Unsaturated Fatty Acid, 20:5n-3 increase with increasing photon flux density in *Gracilaria* species [67].

2.4. Brown algae

2.4.1. Sargassum horneri

Sargassum horneri a brown macroalgae has been the optimal growing temperature of 25 °C and an irradiance of 20 μmol m^{-2} s^{-1} for their early stages. The growth rate of the *S. horneri* was observed 4.6% d^{-1} at 1 meter water depth. Maximum irradiance at the water surface was about 200 μmol m^{-2} s^{-1} [68].

2.4.2. Undaria species

The optimal temperature for the growth of *Undaria pinnatifida* gametophytes is approximately 15–20 °C and temperature is positively correlated with the irradiance within 10–80 μmol m^{-2} s^{-1}. Growth of *U. pinnatifida* gametophyte increased with increasing day length (8, 12 and 16 h). Best growth occurs at 16 h day length under the mean daily irradiance (MDI) of 20 μmol m^{-2} s^{-1}. Vegetative growth and sporophyte production of gametophytes were better at 60 μmol m^{-2} s^{-1} than at 30 μmol m^{-2} s^{-1} under an 8:16 h light: dark and their growth and maturation were density-dependent in 16:20 and 12:12 day length, respectively [69].

2.4.3. Nitzschia species

Three different species of benthic algae *Nitzschia thermalis, Nitzschia laevis, Navicula incerta* are used to determine the effect of white and blue color monochromatic light. These species grown in Erlenmeyer flasks of 250 ml under a constant photon fluence rate (PFR) of 150 μmol m^{-2} s^{-1}, temperature 22 ± 1 °C and salinity 34 ± 1 PSU and f-Medium was used. It was observed that blue light not significantly affected the growth rate. Growth rates obtained from *N. thermalis was* 0.35 d^{-1} and from *N. incerta* to 0.11 d^{-1} Photosynthesis by all the strains was saturated at 800 μmol m^{-2} s^{-1} and photoinhibition was detected at 1600 μmol m^{-2} s^{-1} of PFR [70].

2.5. Phytoplanktons

2.5.1. Euglena gracilis

Euglena gracilis is unicellular flagellate protist. Investigator observed optimum temperature was 27–31 °C for high multiplication rate of *E. gracilis*. Fluorescent lamps used as a source of continuous lighting for 24 h in the range of 20–200 μmol m^{-2} s^{-1} photosynthetic photon flux (PPF) for the culture of *E. gracilis*. Three times more specific growth rate obtained at 50 μmol m^{-2} s^{-1} irradiance than 20 μmol m^{-2} s^{-1}. The maximum specific growth rate obtained at 100 μmol m^{-2} s^{-1} and decreased when the PPF was increased beyond μmol m^{-2} s^{-1} [71].

2.5.2. Prorocentrum species

These Investigator has been studied the effects of temperature, salinity and irradiance on *Prorocentrum donghaiense* growth. The optimum irradiance for growth of *P. donghaiense* was >30 μmol m^{-2} s^{-1}. A moderate specific growth rate of 0.33 d^{-1} was observed at 2 μmol m^{-2} s^{-1}, the minimum irradiance in the experiments and photoinhibition did not occur up to 230 μmol m^{-2} s^{-1}, the maximum irradiance in the experiments. Different salinity and temperature are applied to see the maximum m specific growth rate. The maximum specific growth rate of *P. donghaiense* was0.77 d^{-1} at 27 °C temperature and salinity of 30 psu [72]. Cell division rates of *Alexandrium affine, Prorocentrum rhathymum* and *Prorocentrum shikokuense* monitor at four different temperatures (measured by immersing a probe-type thermometer into the culture medium set at 15, 20, 25 and 30 °C $\pm$ 0.1). Each culture strain was inoculated into one of four autoclaved glass flasks containing a total volume of 200 ml sterilized f/2 medium. These culture flasks were initially maintained at stable conditions of PFD 100 growth (12:12 h light:dark), 33 PSU salinity and 25 °C $\pm$ 0.1 for 3 days prior to the growth experiment. To reduce the likelihood of a shock due to a

sudden temperature shift, the flasks assigned to the remaining temperatures, except 25 °C, were acclimated with an increase or decrease at a rate of 2 °C each day until the designated temperatures were reached. Growth of *P. rhathymum* observed from 15 °C to 30 °C. The growth curves suggested the optimum condition for growth was 25 °C with a cell division rate of 0.62 d^{-1}. Each acclimated culture was maintained at one of the above temperature regimes for 3 days. *A. affine* exhibited low tolerance for the low temperature regime (15 °C) [73].

2.5.3. Scrippsiella trochoidea

Scrippsiella trochoidea, a photosynthetic dinoflagellate were studied under high light irradiance: 70 μmol m^{-2} s^{-1} and low light irradiances: 4 μmol m^{-2} s^{-1} and iron concentrations (low iron: 0.063 mg l^{-1}, medium iron: 0.63 mg l^{-1} and high iron: 6.3 mg l^{-1}) observed various parameters. The maximum values of specific growth rate, OD680 and chlorophyll *a* content were 0.22 d^{-1}, 0.282 and 0.673 mg l^{-1} respectively. High light and high iron concentration may promote algal growth and pigment biosynthesis [74]. *Gyrodinium instriatum* is euryhaline organism that can live under extremely low salinity. *G. instriatum* was investigated under 45 different combinations of temperature (10–30 °C) and salinity (0–40) under saturating irradiance, maximum growth rate of *G. instriatum* was 0.7 d^{-1} at 25 °C and 30 psu salinity. Optimum growth rates (>0.5 d^{-1}) observed at temperatures ranging from 20 to 30 °C and at salinities from 10 to 35. The organism could not grow at ≤ 10 °C. *G. instriatum* burst at a salinity of 0 at all temperatures, but grew at a salinity of 5 at temperatures between 20 °C and 25 °C. Saturated irradiance for growth (I_s) was 70 μmol m^{-2} s^{-1}, which was lower than I_s for several other harmful dinoflagellates (90–110 μmol m^{-2} s^{-1}) [75]. *Alexandrium fundyense*, a dinoflagellates produced toxin and cause shellfish poisoning. Experimental treatments consisted of five temperatures (5, 10, 15, 20, 25 °C), six irradiance (6, 25, 50, 100, 175, 425 μmol m^{-2} s^{-1}), and five salinity (15, 20, 25, 30, 35 psu) levels. The highest growth rate observed was 0.68 d^{-1} at high irradiance. The average growth was approximately 0.3 d^{-1}. At the low irradiance (6 μmol m^{-2} s^{-1}) and high-temperature (25 °C) treatments the isolates failed to grow. In response to temperature, both isolates displayed the highest growth rates at 15 °C. The compensation irradiance for growth was approximately 15 μmol m^{-2} s^{-1}, above which growth rates generally increased with increasing irradiance [76].

2.5.4. Protoceratium reticulatum

In this paper growth and yessotoxin (YTX) production by *Protoceratium reticulatum*, a dinoflagellate was optimized. The culture used for the inoculation was maintained at 19 ± 1 °C, at a salinity of 34, with irradiance of 165 μmol m^{-2} s^{-1} and under a 12:12 h light:dark period. Experimental ranges of salinity, temperature and irradiance of *P. reticulatum* was 20–30, 15–23 °C and 25–165 μmol m^{-2} s^{-1}. It was found that growth and yessotoxin (YTX) production by *P. reticulatum* was independent. Growth of *P. reticulatum* was not very well at low Irradiance level 25 μmol m^{-2} s^{-1}. The irradiance of 165 μmol m^{-2} s^{-1} had a very positive effect on growth [77]. *P. reticulatum* cells death occurs at a salinity of 5 and 10. Highest cell concentration of *P. reticulatum* was observed in the f/2 media at 15 °C and higher salinities (25 and 30 psu). Growth rates in the exponential growth phase ranged from 0.21 to 0.35 d^{-1} [78].

2.5.5. Ostreopsis cf. ovata

Three strains of *Ostreopsis cf. ovate* (D483, CBA-T, OS2T) used for the experiment. Cultures were maintained at 22 °C, 100 μmol m^{-2} s^{-1}, and a 12:12 h photoperiod, in K/2 culture medium. Growth response was observed over a range of temperatures (14 °C, 18 °C, 22 °C, 26 °C, 30 °C and 34 °C), and day length (9L:15D, 12L:12D and 15L:9D photoperiod) conditions, growth performance were investigated at two photon flux density (PFD) conditions, 50 and 200 μmol m^{-2} s^{-1}. These conditions resulted in a daily PFDs ranging between 1.62 and 10.8 μmol m^{-2} s^{-1}. All combinations of temperature and day length were tested between 14 °C and 30 °C. At 34 °C no strain was survived. Growth of *Ostreopsis cf. ovata* was favorable within a range of 18–30 °C, while best growth were measured at 22 °C and 26 °C. Maximum Growth was obtained at 12:12 photoperiod, whereas it was limited by photon flux density at short day length (9 h) and often showed photo saturation at the longest day length (15 h). Highest relative percentage variation of specific Growth rate of *Ostreopsis cf. ovate* 0.64 d^{-1}, 0.61 d^{-1}, at 18 °C and 50 μmol m^{-2} s^{-1} PFD and 26 °C and 200 μmol m^{-2} s^{-1} PFD and 12 L & 9 L day length, respectively. At 12 L & 15 L day length, maximum relative percentage variation of specific Growth rate 0.43 d^{-1} at 26 °C and 200 μmol m^{-2} s^{-1} PFD. At 26 °C temperature and 12:12 photoperiod highest relative percentage variation of specific Growth rate was 0.83 d^{-1} at 200 μmol m^{-2} s^{-1} PFD [79].

2.5.6. Ceratium species

The effects of temperature, irradiance and photoperiod were observed on growth rates of these two dinoflagellates, *Ceratium furca* and *Ceratium fusus*. At laboratory scale the two species grow at 10 °C to 32 °C. The highest specific growth rate of *C. furca* was 0.72 d^{-1} at 24 °C and 600 μmol m^{-2} s^{-1}. Optimum growth rates (>0.4 d^{-1}) of *C. furca* were observed at temperatures from 18 °C to 28 °C and at irradiances from 216 to 796 μmol m^{-2} s^{-1}. The highest growth rate of *C. fusus* was 0.56 d^{-1} at 26 °C and 216 μmol m^{-2} s^{-1}. Specific growth rate of two microalgae *C. furca* and *C. fusus* was observed under a wide range of light regime (0, 58, 183, 216, 597, 796, 930, and 1128 μmol m^{-2} s^{-1}) and salinity values (27, 30, 34 for *C. furca*; 24, 37, 30 for *C. fusus*) in T5 medium ($N=5$ mM; P = 0.5 mM) at 24 °C. The specific growth rates of *C. furca* and *C. fusus* increased with increasing irradiance from 58 to 216 μmol m^{-2} s^{-1}, decreased in the higher light regimes of 930 and 1128 μmol m^{-2} s^{-1}. The specific growth rates of both *Ceratium* species were clearly decreased at L:D=10:14 relative to those at L:D=14:10 and L:D=12:12. Swimming speed of dinoflagellates also influenced by temperature, light intensity and nutrients. Growth rates were saturated, when light intensity was above 216 μmol m^{-2} s^{-1}, and did not show photo inhibition at irradiances up to 796 μmol m^{-2} s^{-1}. Cell division of the two *Ceratium* species did not occur at <10 °C or >32 °C, their specific growth rates increased with increasing temperature until 28 °C during an extended photoperiod (14:10) compared to a short photoperiod (10:14) [80]. Circadian rhythm in *C. furca* was slightly affected by photoperiod and temperature. The speeds of *C. furca* during light periods were faster than those during dark periods, whereas the speeds of *C. fusus* remained relatively constant [81]. Diurnal changes in morphology of *Ceratium ranipes* were observed. Culture of *C. ranipes* was maintained at 12:12 photoperiod. Unusual finger like appendages developed in the light period and absorbed in the dark period [82]. An increase in the densities of both species was recorded on 5 May showing the maximum cell concentrations of *C. furca* and *C. fusus* 14,800 cells l^{-1} and 49,600 cells l^{-1} was reported respectively. There are two reasons for the increased *Ceratium* population one excess of nutrients and other decreased in salinity (to 27 psu) [83].

2.5.7. Gambierdiscus species

Investigators observed different environmental factors affected the growth of different species of *Gambierdiscus*. Present study examined the temperature (15–34 °C), salinity (15–41) and irradiance (2–664 μmol m^{-2} s^{-1}) on growth of *Gambierdiscus*: *Gambierdiscus australes, Gambierdiscus belizeanus, Gambierdiscus caribaeus, Gambierdiscus carolinianus, Gambierdiscus carpenteri, Gambierdiscus pacificus* and *Gambierdiscus ruetzleri* and one putative new species, *Gambierdiscusribotype* 2. Maximum temperature, salinity and irradiance varied between 26.5 and 31.1 °C, 24.7 and 35 and 50–230 μmol m^{-2} s^{-1} respectively. The

upper and lower thermal limits for all species were between 31–34 °C and 15–21 °C respectively. Only 6–17 μmol m^{-2} s^{-1} required to maintain growth [84].

2.5.8. Tetraselmis chui

Different light intensities and day lengths affected the growth and nutrient uptake of *Tetraselmis chui* strain PLY429 an unicellular alga *T. chui* PLY429 was grown for 28 days under three different light intensities (220, 110, and 73 μmol m^{-2} s^{-1}) and four different light: dark cycles (24:0, 16:8; 12:12; 8:16). Longer day length and higher light intensities resulted in higher biomass production, compared to shorter days and lower intensities. This strain was exposed to only 8 h of light period resulted slowest growth. Day length is an important factor to the growth and nutrient uptake [85].

2.5.9. Isochrysis galbana

Isochrysis galbana contains a high profile of polyunsaturated fatty acids. Lipid content obtained 98 mg l^{-1} from the culture under constant white light and 155 mg l^{-1} from the culture under blue intermittent light. Intermittent light of 24:0 showed better growth than continuous white light with light:dark cycles of 12:12 h. There is a relationship between photon flux density and L:D cycle. Maximum biomass obtained 350 mg $l\,l^{-1}$ at total photon flux 40 μmol m^{-2} s^{-1} (24:0 h L:D) [86]. *I. galbana* CCMP 1324 contain highest contents of saturated and monounsaturated fatty acids (SFA+MUFA) as well as polyunsaturated fatty acids (PUFA) in the early stationary phase. When the temperature was 20 °C and 68 μmol m^{-2} s^{-1} [87]. Total lipids accumulated at a higher rate at 30 °C and slightly decreased in the proportion of non-polar lipids. The proportion of glycosyl glycerides increased but no change in the proportion of phospholipids [88].

2.6. Seaweeds

Investigators identify the effect of temperature and irradiance on growth and photosynthetic activity of *Caulerpa prolifera, Caulerpa Mexicana, Caulerpa scalpelliformis* and all common species in the eastern Israeli Mediterranean. These species have been negative growth rate at 15 °C but optimal at 23–26 °C. Average growth rate 16% at 23 °C and 48% at 26 °C. *C. scalpelliformis* is most sensitive to high irradiance, growth was negative from 60 μmol m^{-2} s^{-1} and above. Photosynthetic rates and photosynthetic parameters generally correlated with growth, irradiance, and temperature conditions found in the natural environments for all three species. Few investigators find out a strong correlation between growth capacity and temperatures and irradiances for *Caulerpa taxifolia* cultured under controlled conditions. The upper range of temperature for positive growth was 31.5–32.5 °C and the lower range was 9–10 °C. The algae could survive below 10–12 °C. In this experiment the optimal irradiances were between 88 and 338 μmol m^{-2} s^{-1}(14 h light:10 h dark [89]. Carotenoid and chlorophyll *a* contents measured under two different growth irradiances [120 μmol m^{-2} s^{-1} (HI 1/4 high growth irradiance) and at 15 μmol m^{-2} s^{-1} (LI 1/4 low growth irradiance)] in four freshwater cyanobacterial strains, *Anabaena cylindrica* Lemm. (Strain number ASW 01033), *A. elenkinii* V. Miller (ASW 01057), *A. torulosa* (Carm.) Lagerh. (ASW 01023) and *Nostoc species* (ASW 042). The temperature was 20 °C and under continuous light supply, standard fluorescent tubes, Philips, TL M 40 W/84 RS was used. Investigator observed an increased weight ratio of zeaxanthin to Chlorophyll-*a* after exposure to high irradiances over several days. Two out of four strains showed higher zeaxanthin amounts on a biomass basis as well. It appears that cyanobacteria enhance their carotenoid pool in response to high light conditions, as increased production of other carotenoids with photo protective abilities has also been observed under high irradiance levels.

Some differences in the acclimation pattern were revealed between different cyanobacteria. *A. torulosa* contained higher amounts of every carotenoid, while *Nostoc* sp. mainly increased zeaxanthin, and myxoxanthophyll. *A. elenkinii* produced exceptionally high amounts of myxoxanthophyll and *b*-carotene under higher irradiances. Anabaena cylindrica generally showed less variation of carotenoids under different irradiances [90]. Photosynthesis–irradiance relationships were determined in the five species of littoral and shallow sub littoral marine benthic green algae of differing morphologies. Each species exhibited a linear increase in photosynthetic rate with increasing irradiance up to a maximum light-saturated value. Full sunlight (1405 to 1956 μmol m^{-2} s^{-1}) inhibited photosynthesis of all species except the thick, optically dense, *Codium fragile* (Sur.) Har. Compensation irradiances ranged from 6.1 μmol m^{-2} s^{-1} for *Enteromorpha intestinalis* (L.) Link to 11.4 μmol m^{-2} s^{-1} for *Ulva lobata* (Kutz) S. and G. and did not reveal a consistent relationship to seaweed morphology. Saturation irradiances were highest for *Chaetomorpha linum* (Mull.) Kutz. (81.9 μmol m^{-2} s^{-1}) and lowest for *C. fragile* (49.6 μmol m^{-2} s^{-1}). Highest net photosynthetic rates were obtained from *U. lobata* (9.2 mg C g dry wt^{-1} h^{-1}), *Ulva rigida* C. Ag. (6.5 mg C g dry wt^{-1} h^{-1}) and *E. intestinalis* (7.3 mg C g dry wt^{-1} h^{-1}). Lowest rates occurred from *C. fragile* (0.9 mg C g dry wt^{-1} h^{-1}) [91]. Photo movement are observed in two brown algae *Scytosiphon lomentaria* and *Petalonia fascia.* Negative phototaxis occurred under photon irradiances of 10–90 μmol m^{-2} s^{-1}, and no movement was observed at 190 μmol m^{-2} s^{-1}. The translocation velocity measured between 10 and 90 μmol m^{-2} s^{-1} ranged from 100 to 200 μmol m^{-2} s^{-1}. No effect was observed at wavelengths of 550 nm and above [92]. The impact of two irradiance levels and two phosphorus concentrations on the growth of three submerged macrophytes: Elodea canadensis (waterweed), Myriophyllum spicatum and Zosterella dubia are investigated. Results showed that higher irradiance (230 μmol s^{-1} m^{-2} vs. 113 μmol m^{-2} s^{-1} at 2 m depth) had significant positive effects on submerged macrophyte growth: increasing seven-fold the number of individuals, the number of species surviving (two-fold), aboveground biomass increased 11-fold, belowground biomass 10-fold increased, and total biomass (11-fold), whereas elevated sediment phosphorus (2.1–3.3 mg g^{-1} vs. 0.7 mg g^{-1} dry sediment) did not have any significant impact. Waterweed increased in numbers of individuals and total biomass under high irradiance while biomass per individual remain the same (approximately 0.02 g). The other species increased both in numbers and biomass per individuals [93].

2.6.1. Other species

14 Algae strains identified from the genus of *Chlorella, Haematococcus, Scenedesmus, Chlamydomonas* and *Chloroccum* were able to grow on centrate. Control light–dark cycle and the light intensities used by these investigators were 30, 100 and 200 μmol m^{-2} s^{-1} and controlled by varying the number of fluorescent lamps. The distance between the lamps and the algae culture are important factors. The light–dark cycles investigated were 4:20 and 24:0. The dark condition was maintained by wrapping with aluminum foil. The highest net biomass was 2.01 g l^{-1} and 1.31 g l^{-1} observed from *Chlorella kessleri, C. protothecoides*, respectively [94].

These Investigators observed the effects of temperature, light intensity and pH on photosynthesis of *S. trochoidea* and *Alexandrium tamarense*. These algae grow on optimal temperature 20–22 °C and optimal pH 7.5–8.0. They could not grow when the temperature was below 10 °C or above 30 °C and pH above 9.5; pH 10.0 was deadly to them. Light intensity observed 400 μmol m^{-2} s^{-1} and 650 μmol m^{-2} s^{-1} respectively for *S. trochoidea* and *A. tamarense* [95]. The effect of temperature (13 °C and 20 °C) and irradiance (low light (LL)= 10 μmol m^{-2} s^{-1} high light (HL)= 137 μmol m^{-2} s^{-1} on the population density of two symbiotic algae was observed. Anemone

contains zooxanthellae (brown anemone) and zoochlorellae (green anemone) and mixed Anemone. Temperature and light have different effects on zooxanthellae and zoochlorellae. Population densities of both algal symbionts are regulated by temperature and light, and the relative abundance of each alga in a host anemone may be shifted with changes in these environmental factors. The anemones were kept for 1 week in an environmental chamber at approximately 13 °C. Under constant light of 5–10 μmol m^{-2} s^{-1} photosynthetically active radiation (400–700 nm) measured with a LiCor cosine corrected sensor. There was a significant increase in the density of zoochlorellae at 13 °C and a significant decrease at 20 °C [96]. Three microalgal species *Selenastrum minutum, Coelastrum microporum f. astroidea* and *Cosmarium subprotumidum are* selected to determine the growth rate over a wide range of light intensities (30–456 μmol m^{-2} s^{-1}) and temperature (15–35 °C), using a 15/9 (light/dark) photoperiod cycle. Maximum growth rate and optimum light intensity and temperature of *S. minutum* was1.73 d^{-1} and 420 μmol m^{-2} s^{-1} respectively. Maximum growth rate and optimum light intensity was 1.64 d^{-1} and 400 μmol m^{-2} s^{-1} for *C. microporum*; 1.00 d^{-1} and 400 μmol m^{-2} s^{-1} for *C. subprotumidum* at 35 °C temperature [97]. Three microalgal species *Phaeocystis globosa, Thalassiosira rotula*, and *P. Donghaiense are* cultured in three light intensities (40, 70 and 150 μmol m^{-2} s^{-1}). It was observed that cell numbers and growth rates of algae vary with different light intensities. In *P. globosa* and *T. rotula* maximum growth rates were found at light intensity 150 μmol m^{-2} s^{-1} and growth rate was0.60 divisions per day in *T. rotula*, 1.17 divisions per day in *P. globosa*. The highest growth rate was found in Prorocentrum *Donghaiense*, at 70 μmol m^{-2} s^{-1} irradiance (0.36 divisions per day) [98]. Short and long duration light curves on microalgae and observed the photosynthetic parameters, relative electron transport rate and light saturation point (E_k). Four microalgal species: *Ulva* species, *C. fragile*, *Ecklonia radiate*, *Lessonia variegate* and two microalgal species: *Chlorella emersonii* and *Chaetoceros muellerii* was selected. Maximum relative electron transport rate increased by a factor of three in *E. radiate* and by factors of 1.25 and 1.23 in *C. emersonii* and *L. variegate* respectively. The light saturation point (E_k) increased by 26 μmol m^{-2} s^{-1} in *C. emersonii* and 20 μmol m^{-2} s^{-1} in *C. muellerii* [99]. *Phaeodactylum tricornutum* UTEX 640 was grown in bubble column and airlift photobioreactors under artificial light (230 μmol m^{-2} s^{-1} light flux at the vessel's surface). The photo synthetically active irradiance on a horizontal plane at the location of the reactors was measured using a quantum scalar irradiance meter (QSL-100 Biospherical Instruments Inc., San Diego, CA, USA). The culture temperature was maintained at 22 ± 1 °C. In the vertical column reactors photo inhibition not occurs under (photo synthetically active daily averaged irradiance value of 1150 ± 52 μmol m^{-2} s^{-1}) [100].

3. Algal growths in wastewater

Microalgae have been capacity to assimilate nutrients, so it is used for tertiary treatment of wastewater. Domestic wastewater is favorable for algal growth since due to high concentrations of all necessary nutrients. Growth of microalgae and cyanobacteria is affected with various physical, chemical and biological factors. Light is often limiting the algal growth. Optimum temperature for the algal growth was 15–25 °C [101]. Some critical parameters which limit the algal cultivation, production and harvesting of algae from wastewater treatment HRAPs. Light is important limiting factor for algal growth. Maximum algal growth rate obtained at the light saturation point. Beyond light saturation point algal growth was inhibited due to photo inhibition. Algal productivity increases with increasing pond temperature up to an optimum temperature above which increasing algal respiration and photorespiration reduce overall productivity. The optimal temperature for maximum algal growth rate under sufficient nutrient and light conditions varies between species to species. For the better growth many algal species have been optimum temperature between 28 and 35 °C [102]. The effect of light and phosphorus was observed on growth and composition of benthic algae. Light effects were much stronger than phosphorus. About ten-fold increase in algal *biovolume* over the 10–400 μmol m^{-2} s^{-1} irradiances. *Biovolume accrual* was light-saturated at 100 μmol m^{-2} s^{-1} (5 μmol m^{-2} s^{-1}). Light effects were diminished by low phosphorus concentrations and phosphorus effects were diminished by low irradiances [103]. Investigator has been observed the growth of *Ankistrodesmus falcatus, Phormidium bohneri* and *Oscillatoria agardhii* with the effect of light intensities from 3 to 650 μmol m^{-2} s^{-1}, and for temperatures from 5 to 35 °C. At temperatures of 20 °C or less, *A. falcatus* showed the best growth; no significant difference existed between *P. bohneri* and *A. falcatus* at 25 °C. At 30 and 35 °C, *P. bohneri P. bohneri* better withstood high light intensities [104].

4. Photo bioreactors

The Algae Raceway Integrated Design (ARID) minimizes diurnal and seasonal temperature fluctuations and maintains temperature within the optimal range between 15 and 30 °C. Algae growth enhanced to the comparison of conventional raceways [105]. *C. sorokiniana* grow increased in synthetic wastewater at temperatures of 40–42 °C and light intensity of 2500 μmol m^{-2} s^{-1} in a photo bioreactor for 5 h daily and efficiently remove ammonium from the wastewater under these conditions better than under normal lower temperature (28 °C) and lower light intensity (60 μmol m^{-2} s^{-1}). It was also reported that *Azospirillum brasilense* promote the growth of *C. sorokiniana* [106]. The optimum temperature for photosynthesis of blue green algae (cyanobacteria) was reported 0–20 °C during June to

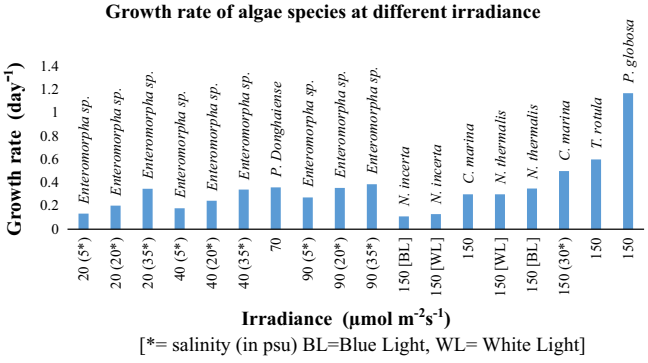

Fig. 1. Growth rate of algae species at different irradiance.

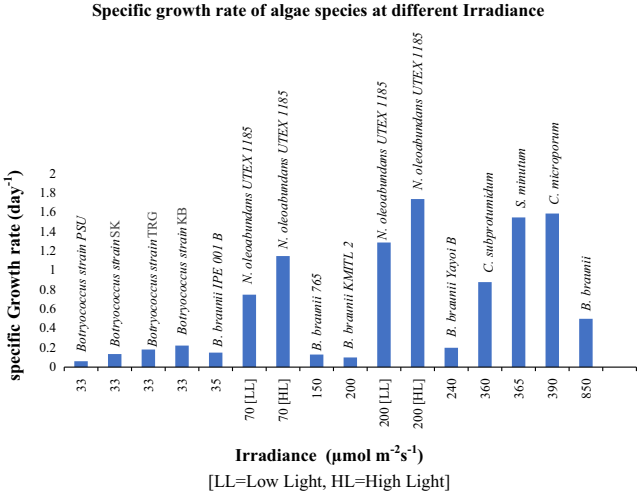

Fig. 2. Specific growth rate of algae species at different irradiance.

November, 20–30 °C in summer. The environmental temperatures were obtained 24 °C in August to 12 °C in November [107].

The variation in growth rate of different algae species were compared with their irradiance levels as shown in Fig. 1. The growth rate of only *N. incerta* was studied in presence of white and blue light. The maximum growth rate of *P. globasa* was at an irradiance level (white light) of 150 $\mu mol\ m^{-2}\ s^{-1}$ among the algae species as reported in this article. The minimum growth rate of *N. incerta* was at an irradiance level (blue light) of 150 $\mu mol\ m^{-2}\ s^{-1}$

The variation in specific growth rate of different algae species were compared with their irradiance levels as shown in Fig. 2. The maximum specific growth rate of *N. oleoabundans* UTEX 1185 was at an irradiance level (high light) of 200 $\mu mol\ m^{-2}\ s^{-1}$ among the algae species as reported in this article. The minimum specific growth rate of *Botryococcus* strain PSU was at an irradiance level of 33 $\mu mol\ m^{-2}\ s^{-1}$.

The growth rate and specific growth rates of all algae species have not been mentioned in the reviewed research publication as depicted in the above mentioned figures.

5. Conclusion

The present study focuses on different algae species grow at different temperature, photoperiod and light intensity. The results of suitable environmental conditions of temperature and light levels were reported for the growth of different algae species. Green algae contains major light harvesting pigments (chlorophyll-*a* and *b*). These pigments are sensitive to wavelengths of blue and red light. Better growth of green algae was observed in this region. Algal growth enhanced by increasing the light intensity up to a certain limit. Growth temperature for algae species in the range 5–40 °C was reported. The optimum temperature for photosynthesis of blue green algae (cyanobacteria) was 0–20 °C during June to November and 20–30 °C during summer. Temperature between 22 °C and 35 °C was favorable for growth of microalgae. Maximum specific growth rate of *N. oleoabundans* UTEX 1185 was reported $1.74 \pm 0.03\ d^{-1}$ at 25 °C, Irradiance 200 $\mu mol\ m^{-2}\ s^{-1}$ (high light) and Nitrogen rich medium. Minimum specific growth rate was $0.061\ d^{-1}$ for *Botryococcus* strain PSU at 25 ± 1 °C temperature and 33 $\mu mol\ m^{-2}\ s^{-1}$ irradiance. *C. vulgaris* can grow in temperature range 25–30 °C and also an extreme environment (30–35 °C). *Scenedesmus* species will grow in the ranges from 10 to 40 °C. *Spirulina* species has the ability to grow in temperatures range from 20 to 40 °C, but the temperature affected the protein and carbohydrate levels.

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