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RESEARCH

Developing an economically efficient LED light regime for *Arthrospira platensis* cultivation

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Abstract

Lighting technologies develop rapidly and the energy efficiency of LEDs quadrupled between prices have decreased more than 60% in the last decade. The cyanobacterium *Arthrospira platensis*, commercially known as food supplement Spirulina, has great potential for urban indoor farming due to its high growth rate and low resources needed. This study investigates the combined effects of photoperiod (16–24 h light), light intensity (100–400 μmol photons m^{-2} s^{-1}), and temperature (27–35℃) on production and energy efficiency in the cultivation of *A. platensis* in 0.5 L bubble column photobioreactor. This study aimed to develop a cost-efficient LED light regime for attaining maximal production of *A. platensis*. All experiments under cold white (6500 K) light show higher light energy efficiency than those under warm white (3000 K) light ($p < 0.05$). The light saturation point was at 261 μmol photons m^{-2} s^{-1} for warm white light and was not reached for cold white light. The maximum specific growth rate (μ_{max}) was 2.2 day^{-1}, 30% higher than reported in the literature. This growth rate was obtained at 24:00 light:dark photoperiod 33–35℃ and cold white light; light efficiency was 3 kW g^{-1} DW. Cultivation under warm white light resulted in 22% lower $\mu_{max,}$ and light efficiency was 9 kW g^{-1} DW. The most economical light intensity was 193 μmol photons m^{-2} s^{-1} of cold white light.

Keywords Microalgae · *Arthrospira platensis*; Spirulina · Artificial light · Energy efficiency · Light intensity

Introduction

Lighting technologies have developed rapidly, reducing energy consumption. The average energy efficiency of LEDs quadrupled between 2009 and 2015, and prices have decreased by more than 60% comparing 2010 and 2017 (McPhie and Rietdorf 2021). This development opens the economically affordable use of artificial lighting indoors for, e.g., basil, parsley, dill, and microalgae (Litvin and Currey 2019). While about 50% of the world's light sources were LEDs in 2019, this percentage is anticipated to increase to about 87 percent by 2030 (Placek, 2021). High-quality LED lights last 25 times longer than incandescent lights while using at least 75% less energy (Palcek 2021).

Growing urbanization and rising demand for high-quality and local food are some of the key reasons driving the urban farming industry. The largest urban farming companies are Spread Co. (Japan), Green Spirit Farm (USA), American Hydroponics (USA), and Shy Greens (Singapore). Spread Co. produces approximately 20,000 lettuce heads every day (https://www.industryarc.com/Report/15491/urban-farming-market.html). While leafy greens are a popular urban indoor farming product, microalgae, e.g., Spirulina (*Arthrospira platensis*), is still cultivated under the sunlight in traditional shallow pond systems. Due to its fast growth rate, low resource needs, and high nutrition value, *Arthrospira* is a promising indoor farming organism. In addition, indoor farming would ensure higher cultivation parameter control and, thus, better and consistent product quality.

The productivity of microalgae biomass and valuable compounds in biomass can be increased under optimal lighting conditions, meaning light intensity, duration of lighting, and spectral composition. Traditionally, Spirulina is cultivated in shallow ponds under sunlight in tropical and subtropical regions (Vonshak and Guy 1992; Afroz and Singh 2021). Outdoor cultivation relies on sunlight, which is the cheapest light source. Therefore,

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it makes outdoor cultivation cost-effective but also dependent on environmental conditions. There are some limitations (1) the amount of sunlight is limited in cloudy regions, like most of Europe (2) the diurnal cycle is closer to the equator or close to the 12:12 light: dark period, while studies show that longer light period, e.g., 16:8 can give higher biomass yield (Ahsan et al. 2008) (3) ponds are shallow and can absorb the air pollution (Vonshak and Guy 1992). Thus, indoor cultivation under artificial lighting could be a solution for consistent quality products due to well-controlled light-temperature-mixing parameters. For indoor microalgae farming, light-emitting diode (LED) technology has emerged as a possible replacement for conventional lighting sources. LEDs have several benefits, including a long lifespan, excellent energy efficiency, and the capacity to emit particular light wavelengths (Trivellini et al. 2023). Due to these qualities, LED lighting is a crucial part of creating energy-efficient culture systems that optimize light regimes and achieve energy savings. Furthermore, a closed system prevents pollution and culture loss due to contamination. Such a solution could be economically advantageous for the Nordic countries, e.g., northern Europe, Canada, and the northern states of the USA. Additionally, indoor farming can be a solution to produce food-grade microalgae locally, sustainably, and in high quality, which is announced as one of the main goals of the Europe Commission Farm-to-fork Strategy https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en. Compact urban indoor farms are one of the solutions to reverse the loss of biodiversity and feed the increasing population without increasing the area of agriculture.

This study investigates the combined effects of light length cycles, light intensity, and temperature on production and energy efficiency in *A. platensis* with the aim of a cost-efficient LED light regime for attaining maximal production of *A. platensis*.

Materials and methods

Microalgae cultivation

This study initially used seven different *Arthrospira* strains (SAG 257.8; SAG 21.99; SAG 85.79; SAG 49.88 from The Culture Collection of Algae at the University of Göttingen, Germany (SAG); PCC 9108 and PCC 7345 from The Pasteur Culture Collection of Cyanobacteria (PCC). The algae were grown in the Zarrouk medium of the composition (L^{-1}): 16.8 g $NaHCO_3$, 2.5 g $NaNO_3$, 1.0 g K_2SO_4, 1.0 g NaCl, 0.5 g K_2HPO_4, 0.04 g $CaCl_2$, 0.08 g Na_2EDTA, 0.2 g $MgSO_4{\cdot}7H_2O$, 0.01 g $FeSO_4{\cdot}7H_2O$ and 1.0 ml of trace elements (L^{-1}): 2.86 g H_3BO_3, 0.02 g $(NH_4)6Mo_7O_{24}$, 1.8 g $MnCl_2{\cdot}4H_2O$, 0.08 g Cu_2SO_4, 0.22 g $ZnSO_4{\cdot}7H_2O$.

The setup is shown in Fig. 1. *Arthrospira* was cultivated in 0.5 L PET bubble columns (diameter 50 mm) with 0.4 L working solution at various temperatures. The temperature was monitored by the setup booth insulation (opening and closing ventilation channels) in the bubble column. Air was bubbled through a ceramic diffusor at a rate of 3.5 L min^{-1}. The gas hold-up was 0.04. The light intensity was regulated by the distance between the light source and the bubble columns according to the basic rule: light intensity decreases inversely proportional to the square of the distance. Biomass was harvested by 35 µm screen, washed with distilled water, and dried in an oven at 40˚C. The specific growth rate μ was calculated using formula: $\mu = (ln(X_2)—ln(X_1)) / (T_2—T_1)$; where X_2 is the final biomass at time T_2; X_1 is the initial biomass at time T_1 (Vonshak 1997).

The dissolved oxygen was measured using a Lutron Dissolved Oxygen Meter PDO-520. The dissolved oxygen was less than 130% of air saturation for all measurements and thus was not discussed as oxygen oversaturated environment was not reached.

Light and light spectrum

The light spectra (Figs. 2) were measured for ten various 24 V LED strips by Ossila Vis–NIR Spectrometer, Model G2001A1. Manufacturer data of LED strips are shown in Table 1.

Two types of LED strips were used for further experiments: warm white (3000 K, 18 W m^{-1}, 2430 lm m^{-1} 12 V) and cold white (6500 K, 18 W m^{-1}, 2430 lm m^{-1}12 V). Bubbling columns were placed at

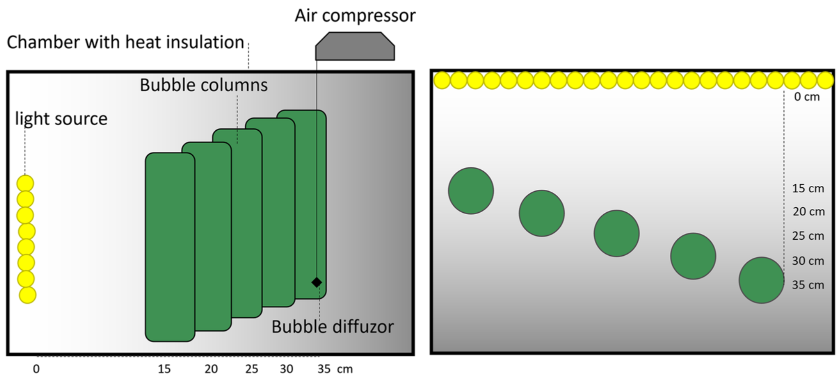


Fig. 1 The experimental setup

various distances from the light source (0.15–0.35 m) for different light intensity effects. Various photoperiods were applied. The initial concentration of inoculum was 2.60 g DW L^{-1}. Biomass was harvested every 3rd day. Microscopic analysis was used to follow any changes in cell morphology. Light intensity was measured with the Digital Lux Meter TASI TA8130 digital light meter (0–100,000 lx). The obtained lux values were converted to PPFD divided by conversion factor 63 for cold white light and 70 for warm white light (Sharakshane 2018).

Light intensities, photoperiod, cultivation duration, and growth rates were analyzed. Various photoperiods (8:4 h; 10:2 h; 16:8 h; 20:4 h; 24:0 h) were used.

Statistical analysis

A logistic fit was used to plot changes in specific growth rates and economic factors through increasing light intensity. Due to the properties of the logistic growth curve, the inflection point between the maximal growth at *xc* and the capacity lies at 75% of *a*, and *k* is a growth coefficient. This value describes the light intensity for optimum growth or optimum efficiency, defined by economic factors.

The used logistic formula to plot the data:

$$y = \frac{a}{1 + e^{-k(x-x_c)}}$$

For analysis of variance, one-way ANOVA testing was used to determine possible significant differences between groups of samples. For the analysis with ANOVA, the significance level was set to $p < 0.05$. In the case of significance, a post-hoc test was performed for multiple comparisons. Here the Tukey test was used. With this distribution, a coefficient q_{observed} was calculated and compared with a so-called critical value, which depends on the chosen α-level, in this case, $p < 0.05$, the degrees of freedom, and the number of means being tested.

For the comparison of two datasets of equal or similar sample-size with each other, a pairwise t-test was utilized. The test was conducted first assuming equal variance and then with the Welch correction without assuming equal variance. At a *p*-value lower than 0.05, the compared means of the selected datasets were significantly different.

Results

Growth rate

Six *Arthrospira* strains (SAG 257.8; SAG 21.99; SAG 85.79; SAG 49.88; PCC 9108, and PCC 7345) were initially compared for growth rate at various temperature, photoperiods, and light intensity. However, no significant response to light was found, so in reported experiments, only PCC 9108 is shown.

The maximal specific growth rate of 2.34 ± 0.07 day^{-1} was obtained at cold light under continuous light at 33—35 °C (Fig. 2C). White cold (6500 K) and warm light (3000 K) effects were studied for 24:00 and 16:08 h and different light intensities and temperatures (Fig. 2). The lowest specific growth rate was observed under the lowest light intensity and lowest temperature (below 120 µmol photons m^{-2} s^{-1} and 27 °C) for both photoperiods. In contrast, the highest growth rate was obtained at continuous light at maximal intensity (Fig. 2A and B). The difference between specific growth rates at temperatures increased with light intensities reaching 35%, with p-values below 0.05 for CW and WW. With an exception between 35 and 33 °C, where similar results for CW light at light intensities above 220 µmol photons m^{-2} s^{-1} (Fig. 2B and D) resulted in no significant difference in growth (*p*-value: 0.35). Cultivation at a 24 h photoperiod resulted in significantly higher growth rates than with 16 h (*p*-value WW [16 h] to WW [24] < 0.0001 *p*-value CW [16 h] to CW [24] < 0.0001. CW [16 h] to WW [16 h] did not differ significantly (*p*-value: 0.24). No significant differences were found for split light, e.g., between 16:08 h and 08:04 photoperiods and between

Table 1 LED strip characteristics

No	Power, W m^{-1}	Brightness, lm m^{-1}	Luminous Efficiency, lm W^{-1}	Light temperature, K	Producer
212,597	12	1680	140	4000	V-TAC
212,598	12	1680	140	6500	V-TAC
212,599	18	2430	135	3000	V-TAC
212,600	18	2430	135	4000	V-TAC
212,601	18	2430	135	6400	V-TAC
321	15	1600	106	4500	V-TAC/ SAMSUNG
322	15	1600	106	6500	V-TAC/ SAMSUNG
331	18	1500	83	3000	V-TAC/ SAMSUNG
332	18	1500	83	4000	V-TAC/ SAMSUNG
333	18	1500	83	6400	V-TAC/ SAMSUNG

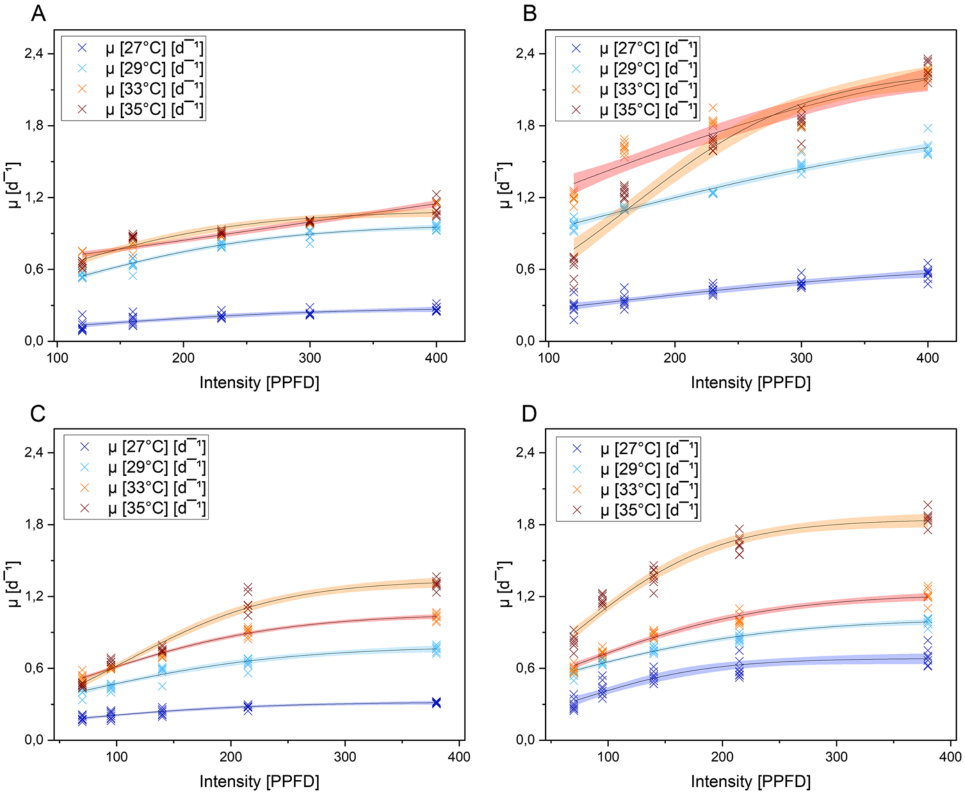


Fig. 2 Specific growth rate at various light intensities and temperatures of *Arthrospira platensis* cultivated under warm white light 16:08 h light: dark period (**A**) and 24:00 h (**B**) and under cold white light 16:08 h (**C**) and 24:00 (**D**). Comparison of all data via ANOVA: F(3,160) = 8.9, $p < 0.05$

20:04 h and 10:02 h photoperiods; thus, detailed data were not reported. pH throughout all experiments was 9 at the start and increased to 10 in a few days.

LED spectra

The spectrum of various LED strips was measured (Fig. 3). The spectrum was similar for both tested warm white (light temperature 3000 K) strips and for all cold white (6500 K) strips, independently from power or brightness. The main difference between the cold white (CW) and warm white (WW) spectrum was the proportion of blue light peak at 460 nm versus the broad peak group at 500–650 nm (corresponding to the green-yellow–red light range).

Discussion

Growth

The white light spectra, intensity, photoperiod, and cultivation temperature can significantly affect *Arthrospira* growth rate. In this study, the maximal specific growth rate of 2.34 ± 0.07 day^{-1} was obtained. In contrast, most of the studies reported a specific growth rate below 0.4 day^{-1} (black dots in Fig. 4, for more details, see supplementary file Table 1, the experimental results of this study are shown by yellow and

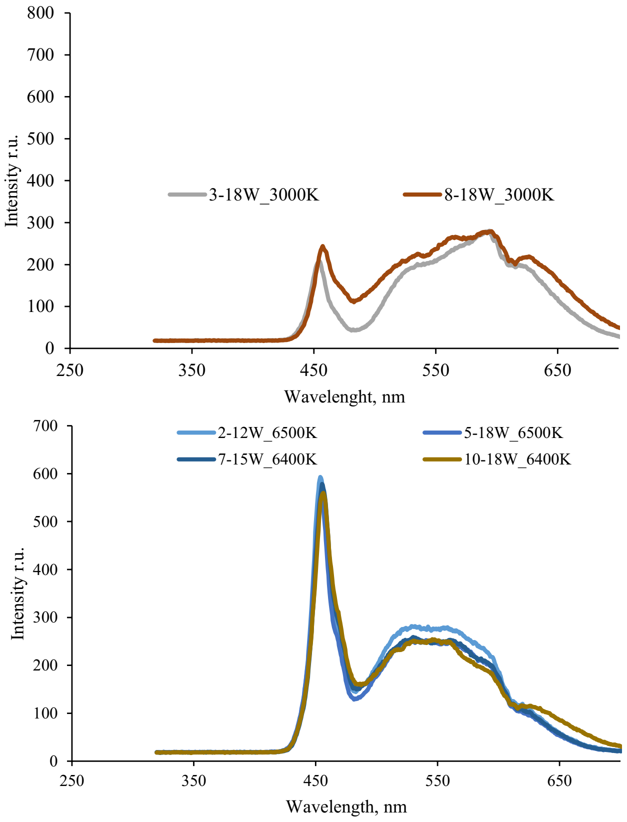


Fig. 3 The spectra of CW and WW LED strips, producers' specification of strips given in Table 1

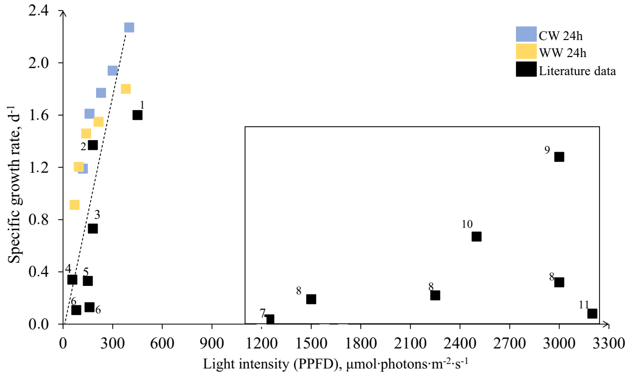


Fig. 4 Specific growth rate of *A. platensis* as a function of light intensity. Numbers refer to the literature: 1 – Xue et al. (2011) photoperiod reported: 24 h; 2 – Socher et al. (2014) 16 h; 3 – Joshi et al. (2018) 16 h; 4 – Zhu et al. (2020) 12 h; 5 – Rizzo et al. (2015) 16 h; 6 – Niangoran et al. (2021) 24 h; 7 – Qiang et al. (1996) 8 h; 8 – Wang et al. (2007) 16 h; 9 – Chen et al. (2010) 16 h; 10 – Soni et al. (2019) 12 h; 11 – Prates et al. (2018) 12 h. The studies in the frame aimed to stress *A. platensis* and produce higher levels of phycocyanin instead of high growth rates. The dotted line is a guideline for an eye for a specific growth rate – light intensity trend

blue dots (growth curves are given in supplementary file)). The maximal specific growth rate obtained in this study was 30% higher than the highest growth rate reported in the literature. Xue et al. (2011) reported 1.6 day^{-1}; however, at slightly higher intensity (450 µmol photons m^{-2} s^{-1}) and continuous light period, the used white light spectrum was not reported.

The specific growth rate was higher at high light intensities of CW light than at WW light. Three pigments ensure light harvesting in *Arthrospira* – chlorophyll *a*, carotenoids, and phycocyanin (Akimoto et al. 2012). CW light spectra showed lower emitted light in phycocyanin respective wavelength (610–630 nm (Ma et al. 2022)) and higher in carotenoids absorption range (400–500 nm (Udensi et al. 2022)). Aouir et al. (2017) report that besides the protection role, carotenoids are accessory light-harvesting pigment of *Arthrospira*, in contrast to their role in green algae as protection pigment only. Both types of LEDs emit very low light at chlorophyll, *a* respective absorbance range – 430 and 663 nm; the peak of the emitted light is at 450 nm light is respective for chlorophyll *b*, but *Arthrospira* does not contain chlorophyll *b*. Akimoto et al. (2012) found that the growth rate under white light (Fluorescent and LED) is higher than under a single blue, green, yellow, or red light. Blue light is mainly absorbed by chlorophyll and carotenoids, while yellow and red light by phycobilisomes (Akimoto et al. 2012).

The saturation irradiance was reached at 261 µmol photons m^{-2} s^{-1} in WW light experiments and was not observed for CW light up to 400 µmol photons m^{-2} s^{-1}. This suggests that *A. platensis* can absorb more CW light than WW light. At the light intensity of 261 µmol photons m^{-2} s^{-1} an optimum of *A. platensis* growth, calculated by logistic analysis, was reached for cultivation at 33 °C and 35 °C (Fig. 2). Vonshak (1992) reported that the saturation irradiance for three *Arthrospira* isolates was 115–165 µmol photons m^{-2} s^{-1}) and that salt stress increases the saturation irradiance from 160 to 250 µmol photons m^{-2} s^{-1}, Li et al. (2021) reported higher light intensity for Spirulina light saturation point—at µmol photons m^{-2} s^{-1}, while Ruengjitchatchawalya et al. (2002) reported about 782 µmol photons m^{-2} s^{-1}. The specific conditions of each experiment like temperature, bioreactor, photoperiod etc., can impact the observed light saturation point. In addition, it can be affected by other growth parameters, like nutrient availability, pH, and temperature, that cause stress (Vonshak and Guy 1992). Designing effective photobioreactor systems and maximizing biomass output requires understanding *Arthrospira* saturation point. *Arthrospira* production may be optimized for resource efficiency, increased productivity, and cost-effectiveness by determining the light intensity at which the microorganism experiences its maximum growth rate without photoinhibition (Susanna et al. 2019).

Arthrospira platensis can be cultivated in a light intensity range from 50 to 3200 µmol photons m^{-2} s^{-1}; the data from the literature are summarized in Fig. 4. Specific growth rate of *Arthrospira* was positively correlated with light intensity up to 400 µmol photons m^{-2} s^{-1}. However, the data distribution is wide and even conflicting; e.g., Chen et al. (2010) and Wang et al. (2007) both cultivated *A. platensis* under the same conditions, but their obtained specific growth rates differed almost four-fold. Secondly, reactor type considerably influences the light distribution and, therefore, the growth rate of *A. platensis*. The incubator shaker employed by Socher et al. (2014) is an excellent example of a well-mixed system that encourages effective nutrient distribution and keeps the cultures environment favorable, reaching a growth rate of 1.37 day^{-1} at 180 µmol photons m^{-2} s^{-1}. In contrast, authors using larger size PBRs reported lower growth rates; for example, only 0.016 day^{-1} growth rate was reached at 6.7-fold higher light intensity (1200 µmol photons m^{-2} s^{-1}) in flat plate bioreactor by Qiang and Richmond (1996) and 0.08 d^{-1} at 3200 µmol photons m^{-2} s^{-1}vertical tubular photobioreactor used by Prates et al. (2018). In small reactors, it is simple to create mixing, which gives the algal cells a consistent environment in terms of light and nutrition and prevents cell settling. However, it is challenging to establish homogeneous mixing in larger reactors because algae encounter changes as the scale of the culture grows, particularly in the hydrodynamic and light aspects (Borowitzka and Vonshak 2017). A few studies used intensity higher than 1000 µmol photons m^{-2} s^{-1}and even higher than the natural sunlight (2000 µmol photons m^{-2} s^{-1}) obtained a relatively low biomass growth rate. These studies were devoted to producing increased levels of phycocyanin by applying light stress.

Most of the reviewed literature used 16 h light period though it is worth highlighting the role of photoperiod in the cultivation of cyanobacteria. Increasing light period length by 30% (from 16 to 24 h), the biomass growth rate increased by 45% (from 1.2 ± 0.03 day^{-1} vs. 2.23 ± 0.03 day^{-1} at 400 µmol photons m^{-2} s^{-1}and 33–35 °C, Fig. 2C and D) for CW light. Such an unproportional increase could be due to avoided dark-period respiration losses under continuous light mode. Higher plants need darkness for their intrinsic internal clock—circadian rhythm (Venkat and Muneer 2022). A plant's circadian clock strongly affects growth, reproductive development, and metabolism (Hsu and Harmer 2014; Seluzicki et al. 2017). In contrast, *Arthrospira* is a simple organism that does not have complex biological systems and processes that regulate the circadian rhythm as in higher organisms (Tidjani et al. 2018). Thus, Spirulina can be successfully grown under continuous light. Although it should be mentioned that the authors' unpublished experiments showed that if the light intensity was too high, being close to photoinhibition, then lack of a dark period can faster lead culture to collapse, as the dark period is the time for repair of photosynthetic apparatus. Artificial light can be well-regulated compared to sunlight. Therefore, a maximal energy-to-biomass ratio should be achieved for maximal resource efficiency and to lower the costs of light. Lower power lights also could decrease the capital costs of lighting systems. Therefore, lower light intensity and more extended photoperiod could theoretically be cheaper than light intensity close to the saturation point, including a dark period for recovery.

Energy efficiency

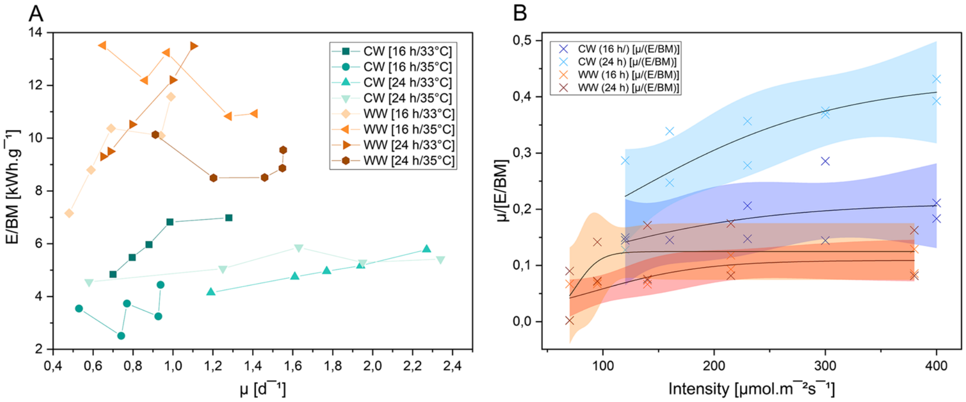
Energy efficiency was higher under CW light than under WW light at all experiments ($p < 0.05$, Fig. 5). Energy efficiency was expressed as light energy E per biomass BM (kWh g^{-1}) (Fig. 5A). Energy efficiency reached 50% difference between the best CW and WW light results (4.5 ± 0.9 and 9.1 ± 0.8 kW g^{-1} CW[24 h/35℃] and WW[24 h/35℃] respectively). In contrast, the growth rate differed only by 22% for the same experiments. The efficiency of WW was lower because WW LED generates less light per the same energy used – 95 and 160 µmol photons m^{-2} s^{-1}at 30 cm distance, WW and CW light, respectively. The energy that is not converted to light is converted to heat. WW LEDs generate 30% more heat than CW LEDs. From an economic aspect, additional costs are required to remove such excess heat.

Energy efficiency was practically the same for all growth rates for CW light 24 h at 33 and 35℃. However, the growth rate differs a lot. Thus, the economic factor (µ E^{-1} BM) was introduced (Fig. 5B). Economic factor was significantly higher for higher light intensities for both white lights at 24 h photoperiod. The logistic fit analysis showed that optimal light intensity for continuous CW light was 193 µmol photons m^{-2} s^{-1}in contrast to 261 µmol photons m^{-2} s^{-1}that was obtained from growth data (Fig. 2). Logistic fit did not apply to 16 h data set, that was too linear—the efficiency does not increase significantly ($p < 0.5$) with an increase of intensities.

The energy efficiency reduced with each day for all light modes (detailed data not shown). Therefore, harvesting Spirulina daily was economically beneficial; all shown data were obtained by harvesting *Arthrospira* daily. Light penetration in the cultivation vessel can explain such semi-batch cultivation efficiency. At low cell concentrations, light penetrates deeper and reaches cells in the deeper layer of PBR, promoting photosynthesis and growth of the cells in the whole volume. In contrast, at higher concentrations, some part of the cultivation tank was a dark zone where respiration occurs, and biomass was lost instead of growth. However, too high dilution can lead to larger PBR volumes to harvest the same amount of biomass per day. Thus, the light source placement respective to photobioreactor geometry, algae concentration, and mixing type and rate plays a crucial role in energy-efficient lighting development. And daily harvesting can ensure lower concentration fluctuations, thus efficient use of photobioreactor volume.

Economic factors are a critical aspect of using LED lights, as it directly impacts the cost of production. Singh

Fig. 5 Energy efficiency (E BM^{-1}) dependence on the specific growth rate of *A. platensis* (**A**) and economic factor (µ E.$^{-1}$ BM) as a function of light intensity (**B**)



and Mishra (2022) have explored that the price of the light-emitting diodes can be decreased by up to 50% by the application of an Arduino-based automated control system to control the power supply to LEDs, photovoltaic powered photobioreactors. Blanken et al. (2013) a decade ago stated that "determined that 4 to 6% of energy from electric input is fixed as chemical energy in microalgae biomass," while Singh and Mishra (2022) already reported that 6–8% of energy from electric input is fixed in the cells. Blanken et al. (2013) already highlighted that the disadvantages of sunlight include day/night cycles, and changes in weather conditions and seasonal changes. However, with the increasing number of people and climate changes, the costs of land and weather changes are increasing factors to evaluate. More compact photobioreactors are costly due to expensive transparent materials and complex geometry. Furthermore, climate changes lead to untypical weather changes, and extreme periods, e.g., hot waves, can lead to culture crush or significantly increase water usage for cooling the system. Avgoustaki and Xydis (2020) argues that indoor vertical farms can produce high-quality and virus-free products that can be locally distributed inside the urban environment where such investments occur, saving millions of tonnes of CO_2 emissions annually. Additionally, Pinstrup-Andersen (2018) names many more reasons to develop vertical indoor farming, to name a few: vegetable availability due to poorly functioning supply chains, pest attacks, droughts, and water scarcity. Thus, closed indoor system photobioreactors equipped with efficient LED light may reduce many risks, save land costs, and be placed in cloudy and cooler areas, e.g., northern Europe – closer to end users. Also, indoor farming is non-seasonal, so from the business aspect, 12 months of non-stop indoor production ensures stable cash flow and thus is a benefit over seasonal agriculture. Combined with the obtained premium quality products, the artificial light costs could be an economically beneficial solution. However, further studies should be devoted to scale-up and develop industrial-size photobioreactors with effective light distribution in larger volumes.

Conclusions

Indoor farming is a rising topic, and fast-growing and highly nutritious *Arthrospira* (trade name Spirulina) is a promising indoor farming species; however, indoor cultivation technology and artificial light setup still need to be investigated. The systematical analysis of the energy efficiency of *Arthrospira platensis* various cultivation parameters (temperature, light intensity and spectra, and photoperiod length) was investigated. Cold white LED lights offer superior growth rate results and biomass production and are more energy-efficient than warm white LED lights. Cold white light promoted a significantly higher growth rate than warm white light under continuous light mode. The light spectra of warm and cold white light differ with the proportion of light at 450 nm and 500 to 600 nm, so the higher intensity of 450 nm wavelength promotes the growth of *Arthrospira*. The obtained specific growth rate was 30% higher than reported in the literature. The maximal specific growth rate of 2.34 ± 0.07 day^{-1} was obtained at cold light under continuous light at 33—35 °C. The highest growth rate was obtained at continuous light at maximal intensity – 400 µmol photons m^{-2} s^{-1}, while the most economical light intensity was at 193 µmol photons m^{-2} s^{-1} and growth rate 1.85 ± 0.06 day^{-1}.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10811-023-03032-w.

Author's contributions ASZ: project management and experimental design, data interpretation, manuscript preparation; SE: statistical expertise, revising manuscript; MB: data acquisition, interpretation of data, manuscript preparation; AB: statistical expertise, interpretation of data.

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Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare that they have no competing interests.

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