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Sunlight potential for microalgae cultivation in the mid-latitude region – the Baltic states

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Abstract. Products, e.g. food and feed from microalgae are a promising part of bioeconomy. One of the most investigated and highly demanded microalgae is *Spirulina*. Light is one of limiting factors for biomass cultivation by photosynthesis. Sunlight is cheap and climate friendly light source. The aim of this study was to evaluate available sunlight potential in the mid-latitude region - the Baltic states (Europe, 55–60 °N) for microalgae, e.g. *Spirulina* growth. The data of Climate atlas based on satellites of EUMETSAT and data from an observation station in Riga were analyzed. The latitude and climate (cloudiness) were main parameters affecting the total solar radiation received by Earth's surface. The sunlight potential in the Baltic states was higher than in most of Europe in similar latitude. Multi-year mean daylight intensity in the Baltic states was slightly less than in Southern France or Bulgaria, (26 klux and 30 klux, respectively, in summer) where *Spirulina* is commercially produced. Hourly solar radiation varied a lot in the Baltic states – from 880 W m^{-2} to 200 W m^{-2}, sunny and overcasted noon of summer day, respectively; average value (8 a.m.–4p.m.) was 450 W m^{-2}. Summer days are longer than 12 h, reaching 18 h in midsummer. The sunlight potential is suitable for microalgae, e.g. *Spirulina* cultivation in this period. From November till February days are shorter than 10 h and solar radiation is less than 300 W m^{-2} even in noon of sunny days.

Key words: Sunlight, solar radiation, microalgae, mid-latitude, Europe, the Baltic states.

INTRODUCTION

The bioeconomy is based on the innovative use of sustainable biological resources to cover the growing demand of food, energy and industrial sectors. In this context, algae represents emerging biological resource (Enzing et al., 2014). From ~ 50,000 microalgae species only 10 are commercially produced. Two most widely investigated and commercially produced species are tropical microalgae *Spirulina* and *Chlorella*. The estimated market value was about 600 million Euro in 2010. Main microalgae market applications are: human (74%) and animal nutrition (25%) and cosmetics (Egardt et al., 2013). Available light is one of the main limiting parameters for biomass cultivation by photosynthesis (Vonshak, 1997; Weyer et al., 2010). The Sun is the cheapest, the most energo-effective and climate friendly light source. However, the position of the Sun in the sky and amount of clouds varies a lot. Closer to the Equator (the low latitude) the Sun in the middle of a day is close to the zenith and it is rising and setting quite more rapidly compared to the higher latitude regions (closer to Earth's poles) where the Sun in the midday is in lower angle and days are longer. The aim of this study is to analyze sunlight potential in Baltic states (the mid-latitude, 55–60 °N) for microalgae *Spirulina*, growth. Another crucial factor for tropical algae is heat, the temperature as part of climate will be roughly overviewed but it will not be discussed deeply due to the limited space of the article.

Solar radiation through atmosphere

The Sun gives full spectra of the electromagnetic radiation. However due to atmosphere mostly visible, near infrared, and near ultraviolet part of spectra reaches Earth's surface (Chen & Julian, 2011). Solar radiation outside the atmosphere is 1,366 W m^{-2}. Under a clear sky reduction of solar radiance that reaches Earth's surface is about 22%. Due to Rayleigh scattering from molecules, especially water and carbon dioxide, and dust particles the short-wavelength radiation is reduced heavily. The reduction is proportional to the inverse power of the wavelength of the radiation. The solar radiation consists of direct and diffuse sunlight. If clouds are present direct sunlight intensity reduces and proportion of diffuse sunlight increases (Chen & Julian, 2011).

The theoretical maximum annual solar irradiance is a function of latitude, e.g. for latitude 0° it is approx. 364 W m^{-2}, for 30°–319 W m^{-2} and for 60°–206 W m^{-2} yearly average. At 60° latitude Earth's surface can receive only 57% of solar radiation that is received at 0° latitude (at the Equator) per year. However due to clouds and other absorptive atmospheric conditions the actual solar energy is reduced, for example, Kuala Lumpur, Malaysia (3° N) receives less energy than Màlaga, Spain (37 °N), 184 W m^{-2} and 197 W m^{-2} respectively (Weyer et al., 2010).

Photosynthesis and light

Light is only a part of the solar radiation spectra that reaches Earth's surface. Light is the part of the solar radiation spectra that is visible for human eye. For photosynthesis only a part of the visible spectra is used. The photosynthetically active radiation (PAR) is commonly defined as 400–700 nm. PAR is 45.8% of total solar energy (Weyer et al., 2010). Actual energy that is available for photosynthesis is determined by pigment types in plants. Photosynthesis is a set of chemical reactions that depends on photon amount, therefore for cultivation of plants photosynthetic photon flux density (PPFD) is used. PPFD is the number of photons (PAR) that fall on a square meter of target area per second (μmol of m^{-2} s^{-1}). The conversion coefficient from light intensity to PPFD (from lux to μmol m^{-2} s^{-1}) varies under different light sources, for sunlight the coefficient is 0.0185 and for cool white fluorescent lamps it is 0.0135 (Apogee Instruments, Inc., Environmental Growth Chambers, 2017). For example, full sunlight is 108 klux or 2,000 μmol m^{-2} s^{-1} on horizontal surface in Malaysia (Taisir et al., 2016) and China (Huang et al., 2017).

How much light do algae need?

Autotrophic microalgae growth in commercial pond is mostly light limited. Photosynthesis in most algal species is saturated at 1/3 the intensity of full solar radiation and in the most cases some photoinhibition is observed at 60–70% of full sunlight (Vonshak, 1987). However other studies have shown that optimal light intensity and optimal cell density are dependent variables. At higher light intensity higher cell density and higher mixing rate is necessary to prevent cells from photoinhibition due to overexposure to light. It is suggested to harvest some part of algae in afternoon for more efficient use of evening light and increase the overall productivity. In thin flat-plate bioreactors (optical path ~ 1 cm) the light intensity can be raised even up to several suns, because cell density is high and intensive mixing moves cells to dark zone of reactor before light causes damage of cells. Therefore, optimal light intensity for each algae strain should be determined experimentally for each growth environment (Richmond & Qiang, 2013). For example, the light saturation point of *Chlorella vulgaris* was 150 µmol m^{-2} s^{-1} in concentration range 0.2 till 1.4 g L^{-1}. The light saturation point of *C. vulgaris* was 30 µmol m^{-2} s^{-1} in concentration range 0.2 till 0.8 g L^{-1}. Photo-inhibition occurred with the high irradiance (200–300 µmol m^{-2} s^{-1}), specific growth rate was much slower for all 10 cultivation days, however it slightly increased after sixth day, probably due to increased concentration above 0.5 g L^{-1} that selfshaded cells (Jiang et al., 2016). The light intensity affects not only the productivity but also the composition of algae, for example, high light intensity (13–28 klux) during the cultivation of *Nostoc muscorum* stimulates the production of carotenoids, while the application of a low light intensity (1 klux) favors an increase in the production and accumulation of phycobiliproteins (Tarko et al., 2012).

The other important parameter of light is the length of photoperiod (light: dark cycle), for example, higher growth rate of *Nannochloropsis sp* was achieved at higher light intensity 350–370 µmol m^{-2} s^{-1} (on the back surface, depth of reactor 190 mm) and longer photo-period 18:6 h comparing to shorter one 12:12 h (Taisir et al., 2016).

MATERIALS AND METHODS

Seasonal changes and differences in various regions of Europe were compared using data on climate; multi-year (1982–2009) mean daylight intensity of seasons (Fig. 1) and global solar radiation and temperatures (Table 1) were taken from Climate atlas. Data in Table 1 was read from Latvia map of Climate atlas. The Climate atlas is based on Satellite Application Facility on Climate Monitoring datasets (CM SAF), new version of PVGIS (autumn 2010). The data used for PVGIS come mainly from geostationary satellites Meteosat, Metop, NOAA. Geostationary weather satellites take pictures of Earth at short intervals (every 15 or 30 minutes).

The solar radiation was analyzed as function of time of the day or year. Various days in the similar solar position was analyzed to find data on clear and cloudy days. The seasons of various years and spring comparing to summer or autumn were compared. Hourly mean solar radiation data of observation station 'Riga-University' is downloaded as a table (date/ hourly solar radiation for every hour) from public database of Latvian Environment, Geology and Meteorology Centre. Location of the station: latitude: 56.9506, longitude: 24.1161. The station is equipped with automatic device and corresponding software for data measurement and observation processing and transmission to the database.

RESULTS AND DISCUSSION

Seasonality

The total daylight intensity including direct, diffuse and reflected sunlight in summer and spring are shown in Fig. 1. In summer multi-year mean daylight intensity in Baltic states wa212qq6tdzddt43s about 65% of that in Mediterranean region, 22–28 klux and 26–40 klux respectively in summer, 16–20 klux and 18–28 klux in spring, 6 klux and 10–18 klux in autumn, 2 klux and 6–18 klux in winter. Due to local climate average light intensity can highly differ in relatively small area. Therefore, the daylight intensity in sunniest areas in the Baltic states were similar to cloudiest areas of Mediterranean region – approximately 27 klux in summer and 19 klux in spring.

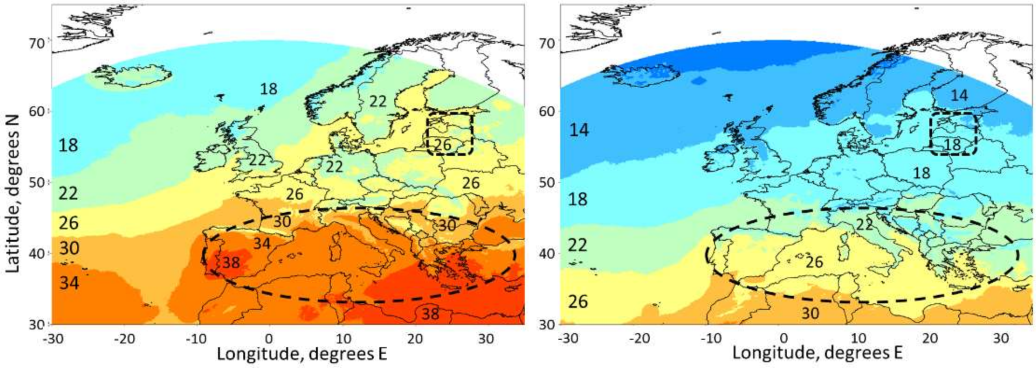

Figure 1. Multi-year mean daylight intensity (in klux) in summer (left) and spring (rigth) in Europe. The Baltic states are shown with square, Mediterranean region with oval shape.

The tropical algae *Spirulina* is successfully grown in commercial greenhouse ponds in Southern France (Spiruline La capitelle) at least for 4 months per year therefore 30 klux average daylight intensity is enough for Spirulina cultivation. In Bulgaria *Spirulina* and *Clorella* are cultivated in photobioreaktor inside greenhouse (bioLEED, 2018). There are also microalgal cultivation ponds of Bulgarian Academy of Sciences, running from March to October in Roupi thermal water region, SW Bulgaria (42 °N). There are 240 sunny days per year in Roupi region (Fournadzhieva et al., 2003). More to the north in the Netherlands (52 °N) is AlgaPARC, microalgae research pilot scale production center where various types of photobioreactors in open air and in greenhouse are running from May to September in open air and greenhouse (AlgaePARC 2014). Spirulina in commercial greenhouses (20,000 sqft) is cultivated also in Richmond, British Columbia, Canada (49 °N) (AlgaBloom Int'l, 2018). The sunlight was slightly less in the Baltic states than in the south of France or Bulgaria, ~26 and 30 klux respectively, but similar sunlight conditions were for the Netherlands and the Baltic States. There was lower cloudiness and higher mean sunlight intensity in the Baltic states than in the north of Germany, Denmark and Great Britain if the same latitude region (Europe, 55–60 °N) was compared (Fig. 3). Therefore the sunlight potential in the Baltic states was higher than in most of Europe in similar latitude.

The sunlight data for winter was not shown due to much lower precision caused by snow and low angle of the Sun above horizon. The main advantage of satellite-based methods is that they give a fairly uniform coverage of large areas comparing to ground stations. But drawbacks of using data from satellites are (1) that snow will look very much like clouds in the satellite images. There are methods to overcome this problem, but the uncertainty is higher in areas with snow (e.g. the Baltic states). (2) When the Sun is very low in the sky the calculation from satellite data becomes very difficult (Help of

PVGIS radiation database, 2017). Therefore, the data shown in Fig. 1. and Table 1 columns: ‘Global solar radiation’ and ‘Light intensity’ lowest precision is for February, March and October when snow covers large part of ground and/or the Sun is low.

Table 1. Multi-year mean meteorological data for Latvia

Month	Global solar radiation, W m^{-2}	Light intensity, klux	Length of day*, h	Sunny (clear sky), h day^{-1}	Average temp, °C	Average max. temp., °C
February	40…60	2...8	10	4…4.5	-7…-3	-4…0
March	80…100	8…12	12.3	6	-2…0	1…3
April	140…180	20...24	14.7	7…8	3…6	7…11
May	200…240	20...28	16.8	9…10	9…12	14…18
Jun	220…260	24...32	17.9	9…11	14…16	18…21
July	200…240	24...28	16.9	9…10	16…18	20…23
August	160…200	20...24	14.7	8…9	15…16	20…22
September	100…120	8...16	12.4	6	10…13	15…17
October	60…80	4...8	10	4…5	5…8	8…11

*21st date, from sunrise till sunset (http://www.suncalc.net/#/56.9496,24.1052,10).

Photoperiod ratio of light:dark at 18:6 h provided better results compared to 12:12 h (Habib et al., 2008; Taisir et al., 2016), thus the length of day that reach almost 18 h in the June and 6 months are longer than 12 h is an advantage.

Statistics of solar radiation was mostly gathered as average value of day, month or year. These data show that solar radiation potential or energy that can be converted in biomass is 2.2 times more in June and July than in March in the Baltic states. However, for algae growth it was also important to analyze diurnal cycle – the length of the day and change of sunlight intensity during the day.

Diurnal cycle

Solar radiation intensity variation during the day were characterized by the hourly mean radiation. The maximal hourly intensity reached approx. 880 W m^{-2} in the middle of the sunny day in June (see Fig. 2). Radiation level above 800 W m^{-2} lasted from 10 am till 1 pm in clear-sky days. Due to the lower angle of the Sun the sunlight intensity was lower in the middle of a day than in tropical countries (1,060 W m^{-2}) therefore cell growth will be less distracted by over exposure to light. Days can be strongly overcast when average hourly radiation in 8:00–16:00 did not exceeded 200 W m^{-2} (6 of 122 days in 2015, May 1st till August 30th) or 300 W m^{-2} (18 days in 2015) (see Fig. 3). Clouds increase the

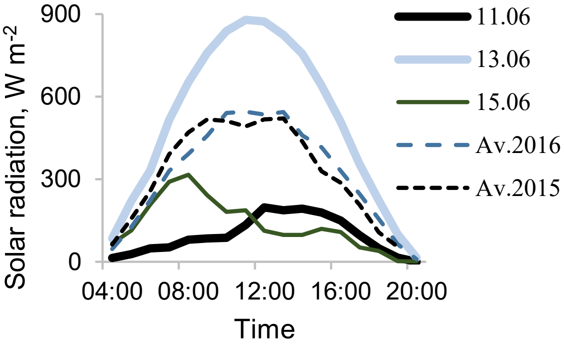

Figure 2. Change of total solar radiation (hourly average) during the day. Data on the sunniest (13.06.2016) and the cloudiest days (11.06.2016 and 15.06.2016) are shown and average values for period June 10 till June 31 in 2015 and 2016.

portion of diffused sunlight that is an advantage in illumination of photobioreactors, e.g. flat plate photobioreactors, because both sides receive similar radiation dose and there is less distinct direct light and shadow sides. Therefore medium cloudiness is an advantage.

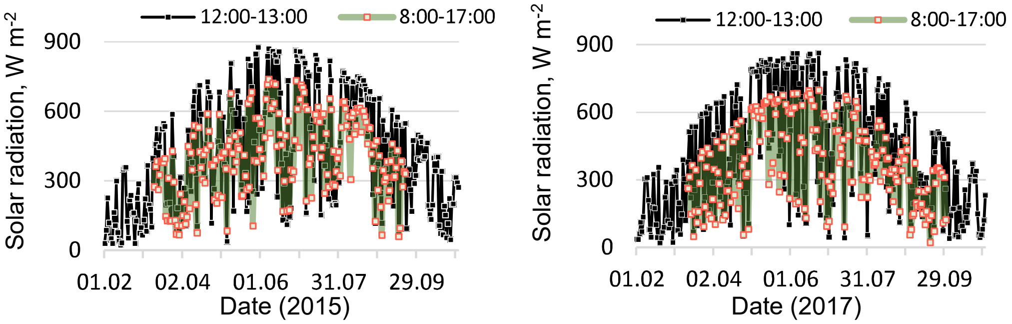

Figure 3. Fluctuation (due to clouds) of solar radiation intensity from February till October.

Maximum solar radiation intensity reached 880 W m^{-2} and was above 800 W m^{-2} from the beginning of May till the end of July, however radiation reached so high value no more than four hours per day and no more than 24 days per year (2015–2017). Average hourly radiation in 8:00–16:00 was approx. 450 W m^{-2} May 1st till August 30th in 2015–2017 that is approx. 42% of full sunlight. Therefore, in this period sunlight was enough for tropical microalgae, e.g. *Spirulina* cultivation. Main challenge for photobioreactor design and cultivation parameter setting will be strong fluctuations of light intensity.

In dark season – from November till February days are shorter than 10 h and solar radiation was less than 300 W m^{-2} even in noon of sunny days. Therefore, this period is too dark for commercial algae growth under sunlight.

CONCLUSIONS

The latitude was not the main parameter affecting total solar radiation received by Earth's surface as it could be expected by the Sun angle calculation. The other important factor that determines the amount of available sunlight was climate or cloudiness. The sunlight potential in the Baltic states was higher than in most of Europe in similar latitude.

The sunlight potential in mid-latitude region (e.g. the Baltic states) is suitable for cultivation of microalgae Spirulina at least four months of year. The advantages of higher latitude are long hours with moderate light intensity; six months with daytime longer than 12 h. The drawbacks are rapid changes of light intensity due to clouds; light intensity can reach the level of overexposure (light inhibition) of microalgae; at least 4 months per year it is too dark to cultivate microalgae under the sunlight.

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