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A novel V-shaped photobioreactor design for microalgae cultivation at low latitudes: Modelling biomass productivities of *Chlorella sorokiniana* on Bonaire

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ABSTRACT

Microalgae are a promising renewable feedstock for a wide range of biobased products, such as food, feed, chemicals, and biofuels. To commercialize bulk products from microalgae, the production costs need to be reduced, for example, by improving biomass productivities in outdoor photobioreactors. Geographical locations near the equator are considered ideal for outdoor cultivation, due to the abundance of sunlight throughout the entire year. However, at high light intensities the photosystems of microalgae become oversaturated, which limits photosynthetic efficiencies and biomass productivities. Therefore, we propose a novel V-shaped photobioreactor to capture and dilute available sunlight at low latitudes. For different V-shaped designs, we modelled the sunlight entering the photobioreactor during several days of the year and theoretically estimated the maximal biomass productivity of *Chlorella sorokiniana* on the island Bonaire (12°N, 68°W) assuming clear-sky conditions and light-limited growth. Our results show that theoretical biomass productivities of 38.3–50.5 g m^{-2} day^{-1} can be achieved in V-shaped photobioreactors, corresponding to photosynthetic efficiencies of 2.5–3.3%. These productivities are up to 1.4 times higher than those estimated for a flat horizontal photobioreactor, primarily due to improved light dilution in V-shaped photobioreactors. Thus, V-shaped photobioreactors present opportunities for more efficient microalgae production.

1. Introduction

In the global transition towards more sustainable and biobased economies, microalgae are recognized as a promising renewable feedstock for biobased products. Their cultivation does not require arable land or freshwater and, in fact, many microalgae naturally grow in brackish and seawater [1,2]. The biomass of microalgae contains lipids, proteins, pigments, and carbohydrates, and can be processed into numerous products, for example in the chemical, pharmaceutical, and food and feed industries [3,4]. However, to commercialize products from microalgae, particularly bulk products, the production costs need to be further reduced to values below 0.6 € kg^{-1} [3]. These costs can be reduced, for example, by improving the biomass productivity in photobioreactors.

The availability of light is an important factor that determines the biomass productivity of microalgae, as light is essential for phototrophic growth [5,6,7]. In photobioreactors, more light typically results in a higher biomass productivity provided that sufficient nutrients and suitable growth conditions, for example in terms of pH and temperature, are available, and microalgal cultures are sufficiently dense and mixed to prevent photoinhibition [5,7,8]. Since the sun is a naturally available source of light, outdoor cultivation of microalgae has received considerable attention in the past decades [9,10,11]. Locations near the equator are considered to be favorable, due to the abundance of sunlight throughout the entire year and the relatively constant temperatures [12,13]. Moreover, the design of the photobioreactor itself is also important in terms of light availability. Depending on the design of the photobioreactor, sunlight can be lost from the reactor due to reflection of light or light capture can be inefficient when sunlight is absorbed by the ground.

Microalgae ultimately convert available light in the culture into chemical energy in the form of biomass. The maximal theoretical

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efficiency of the conversion of sunlight into biomass (i.e. the photosynthetic efficiency) has been estimated to be below 10% for microalgae [5,2]. In practice, much lower long-term photosynthetic efficiencies are obtained in outdoor photobioreactors [2,9]. An important loss in efficiency is caused by the photo-saturation effect [2]. Most microalgae are adapted to light intensities of up to 50–200 μmol PAR photons m^{-2} s^{-1} [6,2,14]. However, the intensity of sunlight around midday can become more than 10 times higher, especially at low latitudes, as well as during the summer at higher latitudes [7,2,12]. Under such high light conditions, the photosystems of microalgae become oversaturated; the systems cannot process the harvested photons at the rate at which the photons are being supplied [2]. As excess photons remain unused and are dissipated, the photosynthetic efficiency decreases. To reduce the photo-saturation effect and to improve the photosynthetic efficiency, incident sunlight needs to be diluted to lower, more favorable light intensities.

Sunlight can be diluted to lower intensities within a photobioreactor when the incident light is redistributed over a larger surface area in the culture [6]. Several approaches exist to dilute sunlight within microalgal cultures. For instance, researchers have investigated systems in which incident sunlight is first concentrated using lenses or mirrors, and subsequently dispersed into the culture using optical fibers or light guides [2,15,6,16,14] Although the illuminated surface area in the culture is significantly enlarged in such systems, the high material and construction costs are a drawback for large-scale application [2,15].

More simple light dilution strategies are based on refraction of incident sunlight at the surfaces of a photobioreactor. The degree with which sunlight is refracted at the reactor surface is dependent on the geometry, or the position of the photobioreactor relative to the sun. The larger the angle of incidence of light with the reactor surface, the larger the degree of refraction. For example, in vertical photobioreactors, incident sunlight is strongly refracted at the surface around noon, allowing the intense midday sunlight to be redistributed over a larger area of the culture and, thereby, to enter the reactor at diluted intensities [17,1]. Although vertical photobioreactors enable higher photosynthetic efficiencies to be achieved during the day [9], the loss of light to the ground in between the reactors remains a limitation [18].

In this paper, we propose a novel V-shaped photobioreactor design to simultaneously dilute incident sunlight and minimize light losses from the reactor. We hypothesize that incident sunlight in a V-shaped photobioreactor is diluted to much more favorable intensities during the day, due to refraction of sunlight at the V-shaped surfaces. In addition, we hypothesize that losses of light are minimized, because a V-shaped reactor completely covers the ground surface, and light can be reflected and trapped within the V-shape itself. We expect that the combined improvements in light capture and dilution enable higher photosynthetic efficiencies and microalgal biomass productivities to be achieved, which potentially lower the overall production costs for microalgae.

In other fields, V-shaped structures have been studied for improved dilution and/or capture of incident light as well. For instance, V-shaped layers or films in solar cells have been described as 'light trapping' geometries, in which incident light is almost entirely reflected internally, instead of being reflected and lost from the system [19,20,21,22]. Furthermore, for microalgal biomass production, stacked V-shaped photobioreactor designs and inexpensive V-shaped covers for raceway ponds have been suggested recently [23]. It was shown that dilution and trapping of incident light allow V-shaped systems to outperform traditional photobioreactors at incidence angles that occur around midday [23].

In this study, we investigate the potential of a novel V-shaped panel photobioreactor design to cultivate microalgae at low latitude locations. To do so, we developed a model to compute the theoretical biomass productivity of *Chlorella sorokiniana* in V-shaped photobioreactors under clear-sky conditions, taking into account the relative position of the sun during the year, the distribution of sunlight over the reactors, and the intensity of the light entering the culture. With our model, we simulated the maximal biomass productivity on different days of the year, assuming clear-sky conditions and light-limited growth. As an example-case for a low-latitude location, we considered that the modeled photobioreactors were located on Bonaire (12°N, 68°W), a tropical island in the Caribbean. We ultimately used the model as a tool to compare different V-shaped photobioreactor designs with each other, as well as with a flat horizontal photobioreactor. The main objective of this study is to illustrate the potential gains in biomass productivity that can be achieved in novel V-shaped photobioreactors at low latitudes as a result of light capture and light dilution.

2. Materials and methods

To study the potential of a novel V-shaped photobioreactor design for microalgae cultivation at low latitudes, we developed a mathematical model in MATLAB R2016b [24] (Fig. 1). For any given moment of the year, the model computes the position of the sun relative to the photobioreactor, followed by the distribution of incident sunlight over the reactor surfaces, and finally the intensity of the light entering the culture. Using this information in combination with the existing microalgal growth model presented in [25], the maximal biomass productivity of *Chlorella sorokiniana* is estimated (Fig. 1). We used our model to compare the theoretical biomass productivity in different V-shaped photobioreactors with each other as well as with a horizontal photobioreactor on several days of the year. Detailed information about the model (Fig. 1), including the equations, can be found in the Appendix A.

In this study, light-limiting conditions were assumed, meaning that light is the primary factor affecting the biomass productivity, while factors such as pH, temperature, mixing, nutrient supply, and dissolved CO_2 and O_2 levels are within an optimal range. This is often considered to be the case in photobioreactors [5,7,14], since the latter parameters can be controlled using specific strategies or process designs, while microalgal cultures are exposed to continuously changing light conditions in outdoor settings. Hence, factors such as pH, temperature, mixing, and nutrient supply were not considered growth-limiting and were not included in the model. The purpose of our model was to provide a tool to investigate and compare the potential biomass productivities in different V-shaped photobioreactor designs as a result of light capture and light dilution. The model results represent the maximal biomass productivities that can be achieved in the modelled photobioreactors assuming light-limited growth under clear-sky conditions.

2.1. Photobioreactor design specifications

The novel V-shaped photobioreactor design that we propose and that we have modeled consists of two panels that are arranged in a V-shape (Fig. 2). One of the panels is inclined towards the north, while the other is inclined towards the south. For convenience, the distance between the plates of the reactor panels (i.e. the depth or thickness) was arbitrarily set at 0.01 m, and the vertical height of the reactor was set at 0.5 m (Fig. 2), which are within a realistic range for flat panel photobioreactors. The diagonal extension of each panel is dependent on the inclination angle and the vertical height (i.e. the panel extension is equal to 0.5/sin(β) m). The height of the reactor does not influence the model results, whereas the depth of the reactor determines the optimal biomass concentration in the panels. Moreover, in our model simulations, we considered a 1-meter long section of an infinitely long reactor (Fig. 2). We compared several V-shaped photobioreactor designs that differ in the inclination angles of the panels (Table 1).

In Fig. 2, a photograph is shown of a prototype photobioreactor with the novel V-shaped design, in which microalgae are being cultivated, as an example of how this system looks like in practice. The system is being tested at Wageningen University at AlgaePARC Bonaire. In the prototype, air and CO_2 are supplied via a sparger at the bottom of the reactor panels, O_2 can escape via the headspace, and mixing is achieved as a result of gas bubbles and circulation of the culture (Fig. 2). Other

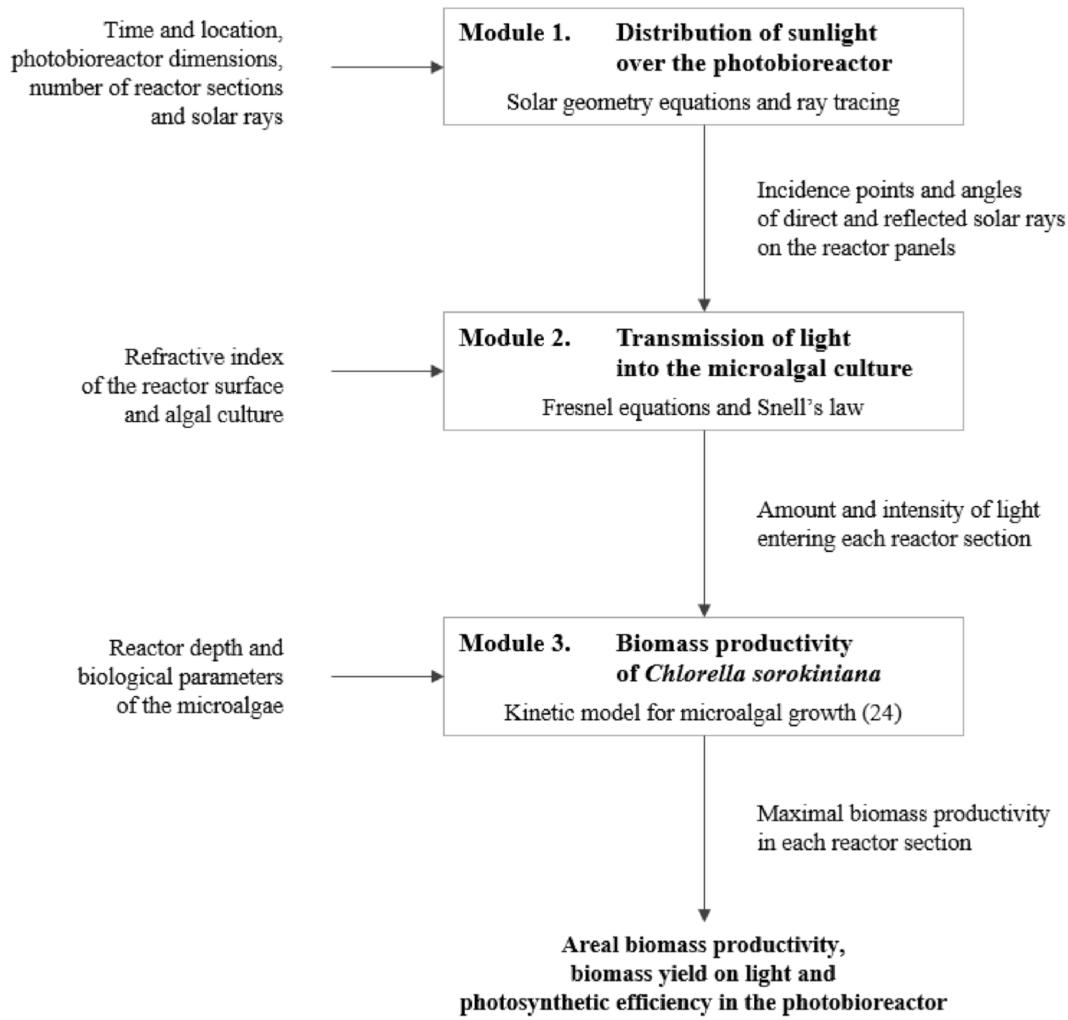


Fig. 1. A schematic overview of the model developed and used in this study showing modules of the model, the inputs, the outputs, and the calculation methods.

conditions including pH and nutrient supply are also controlled, and growth is therefore assumed to be light-limited.

2.2. *Modelling the incident and transmitted sunlight at the reactor surfaces*

To simulate the incident sunlight onto the photobioreactor at a given moment in time, our model first computes the position of the sun relative to the reactor, based on solar geometry equations (Fig. 1 and Appendix A). The model then computes the distribution of sunlight over the glass plates of the photobioreactor. A ray tracing approach is used (Fig. 1), in which all sunlight reaching the reactor surfaces is modelled as a large number of parallel rays (Table 1). Therefore, both the direct and diffuse fractions of sunlight are assumed to be of collimated nature. The direction in which the rays travel is derived from the relative position of the sun with respect to the reactor. The paths of the solar rays as well as their reflected rays are followed to determine if, where, and at which angle they strike the glass surfaces of the photobioreactor. Every solar ray is followed for a maximal of two reflections, as it was found that on average less than 5% of light remains after these reflections. Remaining light was assumed to be lost from the system.

Following the distribution of sunlight over the reactor surfaces, the model computes the amount and intensity of sunlight entering the microalgal culture under clear sky conditions (Fig. 1). In this computation, atmospheric absorption is taken into account and it is assumed that there is no cloud coverage [26]. This is discussed in section 3.4. As sunlight is not equally distributed over the glass plates, the surfaces are divided into a large number of sections (Table 1); in our simulations we divided the photobioreactor arbitrarily in 100 sections (i.e. 50 sections per panel) over which 100 incident solar rays are distributed (i.e. 50 rays per panel). For each reactor section, the model quantifies the transmission and refraction of sunlight at the air-glass and glass-culture interfaces, based on the paths of the incident and reflected solar rays. The degree of transmission and refraction follows from the incidence angles of the rays and the refractive indices of the air, glass and liquid culture (Table 1) through which the light travels, and is calculated using Fresnel equations and Snell's law (Fig. 1 and Appendix A).

2.3. *Estimating the biomass productivity of Chlorella sorokiniana*

To estimate the maximal biomass productivity of *Chlorella sorokiniana* that can be achieved on the transmitted sunlight at a given moment in time (Fig. 1), a function for the biomass yield on light (Fig. 3) was first derived from an existing kinetic model for microalgal growth under light-limited conditions [25].

In the kinetic growth model, the light gradient within a flat panel photobioreactor is calculated using the Lambert-Beer law, based on the spectrum of solar radiation, the reactor depth, and the concentration and the wavelength-dependent absorption cross-section of the microalgae. From the light gradient, the sugar production rate along the depth of the reactor is calculated based on the light saturation curve of Jassby and Platt. This photosynthesis model is combined with the aerobic

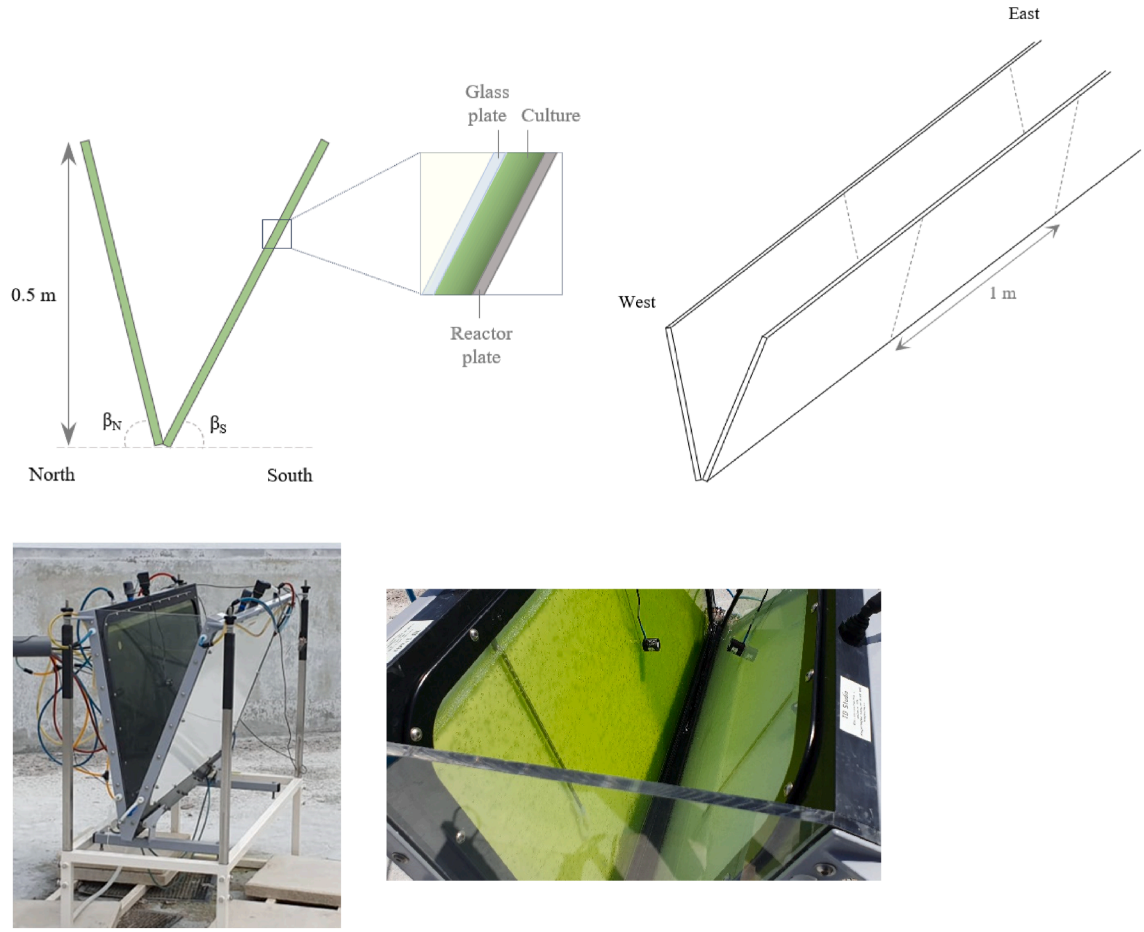


Fig. 2. Schematic drawings of the proposed V-shaped photobioreactor design and dimensions of the modelled reactors (top) and photographs of a prototype photobioreactor with a V-shaped design tested at Wageningen University at AlgaePARC Bonaire (bottom).

Table 1
Overview of input variables.

Variable	Value
Location	Bonaire (12°N, 68°W)
Simulated days of the year	Day 80 (March 21) = day 265 (September 22); Day 120 (April 30) = day 224 (August 12); Day 172 (June 21); Day 304 (October 31) = day 40 (February 9); Day 355 (December 21).
Simulated hours of the day	6:00–19:00 local time
Number of solar rays	100
Reactor height	0.5 *m*
Reactor length	1 *m*
Number of reactor sections	100
Modelled photobioreactor designs	V-shaped photobioreactors with inclination angles β_N, β_S (Fig. 2): 20°, 20°; 40°, 40°; 60°, 60°; 70°, 70°; 80°, 80°; 85°, 85°; 80°, 70°; 80°, 60°. Horizontal photobioreactor
Refractive indices	1 for air, 1.5 for glass, and 1.33 for the microalgae culture
Microalgae species	*Chlorella sorokiniana*

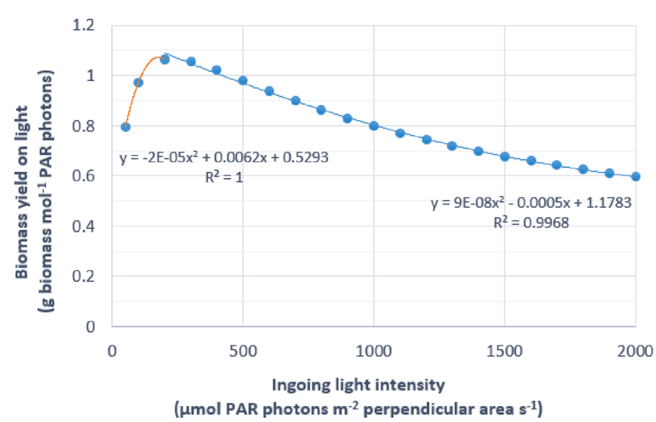


Fig. 3. The biomass yield on light for Chlorella sorokiniana at different ingoing light intensities, obtained using the model presented in [25]. The points in the graph represent individual model simulations, from which continuous functions were derived, which were used to estimate the maximal biomass productivity.

chemoheterotrophic growth model of Pirt to calculate the average specific growth rate of the culture, which takes into account that part of the sugar produced via photosynthesis is used for maintenance of the cells. The inputs for the microalgal growth model were the reactor depth (0.01 m), and the following biological parameters: the maximal biomass yield on light, the maximal growth rate, the sugar yield on photons, the sugar consumption rate for maintenance, and the absorption cross-section [25]. Values for *Chlorella sorokiniana* grown on ammonium as a nitrogen source were used, as provided in [25].

From the average specific growth rate over the depth of reactor, the biomass yield on light of the microalgal culture (Fig. 3) was obtained for different ingoing light intensities, assuming an optimal biomass concentration [5,27]. The optimal biomass concentration was found with the growth model, by means of iteration, as the biomass concentration giving the highest biomass productivity and is defined as the concentration at which the light intensity at the 'backside' of the culture (i.e. the darkest part of the culture) is equal to the compensation point of photosynthesis. At this intensity, the amount of sugar respired for maintenance is equal to the amount of sugar (i.e. glyceralgehyde 3-phosphate) produced through photosynthesis [5]. Hence, an optimal biomass concentrations entails that positive growth is achieved throughout the culture in the reactor, resulting in maximal biomass productivity [5]. An optimal biomass concentration was assumed in order to calculate the biomass yield on light for a range of light intensities (Fig. 3). Using the derived function for the biomass yield on light (Fig. 3), our model estimates the maximal biomass productivity in each section of the photobioreactor at a given moment during the day for a given day in the year (Fig. 1). Thus, all model results were obtained assuming an optimal biomass concentration in each reactor section for each simulated moment in time.

2.4. Comparing the V-shaped and horizontal photobioreactors

We used our model to simulate 5 days of the year, namely day 80, 120, 172, 340 and 355 (Table 1), and estimate biomass productivities in different photobioreactors during the daytime hours of these days. By simulating the 5 days days, we took the relative position of the Sun into account, which changes during the year as a result of the axial tilt and rotation of the Earth (Fig. 4). As such, the changing angle of incidence of sunlight was included in the simulations. Day 80 corresponds to the March equinox and is a day on which the sun reaches a position that is perpendicular to the equator. This day is equivalent to day 265, corresponding to the September equinox (Fig. 4). Day 172 corresponds to the June solstice and is the day on which the sun reaches its most Northern position. Day 355 corresponds to the December solstice and is the day on which the sun reaches its most Southern position. Day 120 is an average day between an equinox and the June solstice in terms of the Earth's declination angle. Similarly, day 304 is an average day between the equinox and the December solstice (Fig. 4). It must be noted that by simulating only the daytime hours (Table 1), a small fraction of biomass that is additionally lost during the night as a result of maintenance processes was not taken into account.

3. Results and discussion

3.1. Daily biomass productivity of *Chlorella sorokiniana* in the horizontal and V-shaped photobioreactors on Bonaire

In the modelled V-shaped photobioreactors, the average biomass

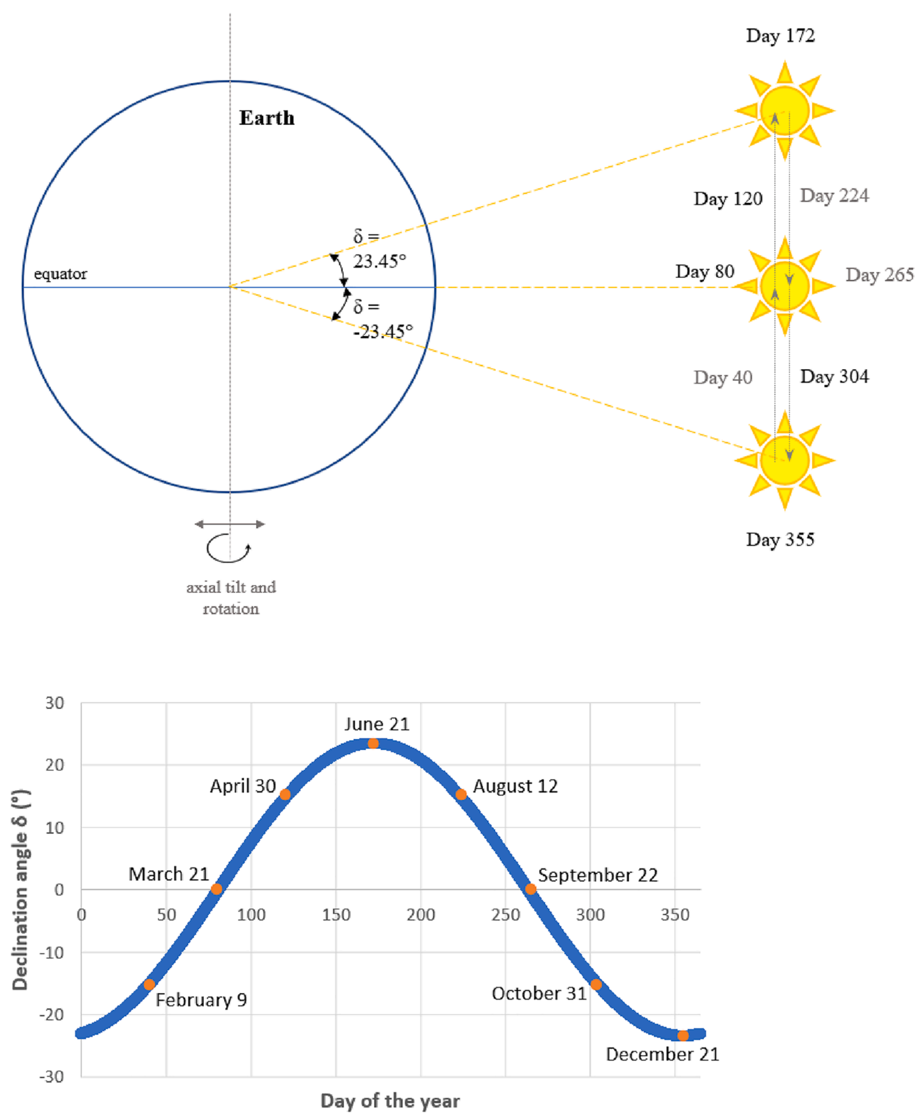


Fig. 4. The solar declination angle varies throughout the year. In our simulations, the indicated days were simulated to consider the changing relative position of the sun.

productivity of *Chlorella sorokiniana* on the simulated days was estimated to be 38.3–50.5 g m^{-2} horizontal area day^{-1} depending on the panel inclination (Fig. 5). In the horizontal photobioreactor, the average productivity on the simulated days was estimated to be 36.4 g m^{-2} horizontal area day^{-1} (Fig. 5). Hence, the modelled V-shaped photobioreactors show a gain in biomass productivity of up to 39% compared to the horizontal photobioreactor. Furthermore, the areal biomass productivity was found to increase with the inclination angles of the reactor panels; the highest areal productivities were found in the V-shaped photobioreactor with panel inclination angles of 85° (Fig. 5).

During the year, the highest productivities were found on day 80 and 120, and the lowest productivities on day 304 and 355. This indicates that lower productivities are achieved during the winter season, when the sun reaches its most southern positions relative to the equator and the location of the reactor (Fig. 4), whereas higher productivities are achieved when the sun is more perpendicular relative to the location of the reactor. The largest differences in biomass productivity between the modelled photobioreactors, and the highest gains for the V-shaped photobioreactors with the largest panel inclination angles, are also seen on day 80 and 120 (Fig. 5). Thus, depending on the day of the year and the corresponding incidence angle of solar rays onto the modelled photobioreactors, the biomass productivity varies (Fig. 5) as a result of the amount and intensity of light entering the reactor.

The average volumetric productivities on the simulated days in the V-shaped photobioreactors were also calculated (Appendix B); these were estimated to be 0.4–3.6 g L^{-1} d^{-1}, of which the highest values were found for the horizontal photobioreactor and V-shaped designs with the smallest panel inclination angles. The volumetric biomass productivity was found to decrease with the inclination of the panels, as the ratio of volume to horizontal surface area of the photobioreactors increases with inclination (Appendix B). It was found that while the biomass productivity per m^2 horizontal surface is higher in V-shaped PBRs with large reactor panel inclinations, the reactor volume or cultivation surface area of these reactors is relatively high, resulting in lower productivities per unit volume (Appendix B). It must be noted that as the cultivation surface area increases with the inclination of the panels, the material use and related costs will also increase. This must be taken into account in future techno-economic assessments of such systems.

3.2. Trapping of sunlight in the V-shaped photobioreactors

Throughout the year, the availability of sunlight is high at low latitude locations such as the island Bonaire (Fig. 6). Based on our model, the available sunlight on Bonaire can amount to 70.5 mol PAR photons m^{-2} during the day on average, assuming clear-sky conditions, i.e. a cloudless atmosphere (Fig. 6). In the presence of clouds, the amount of

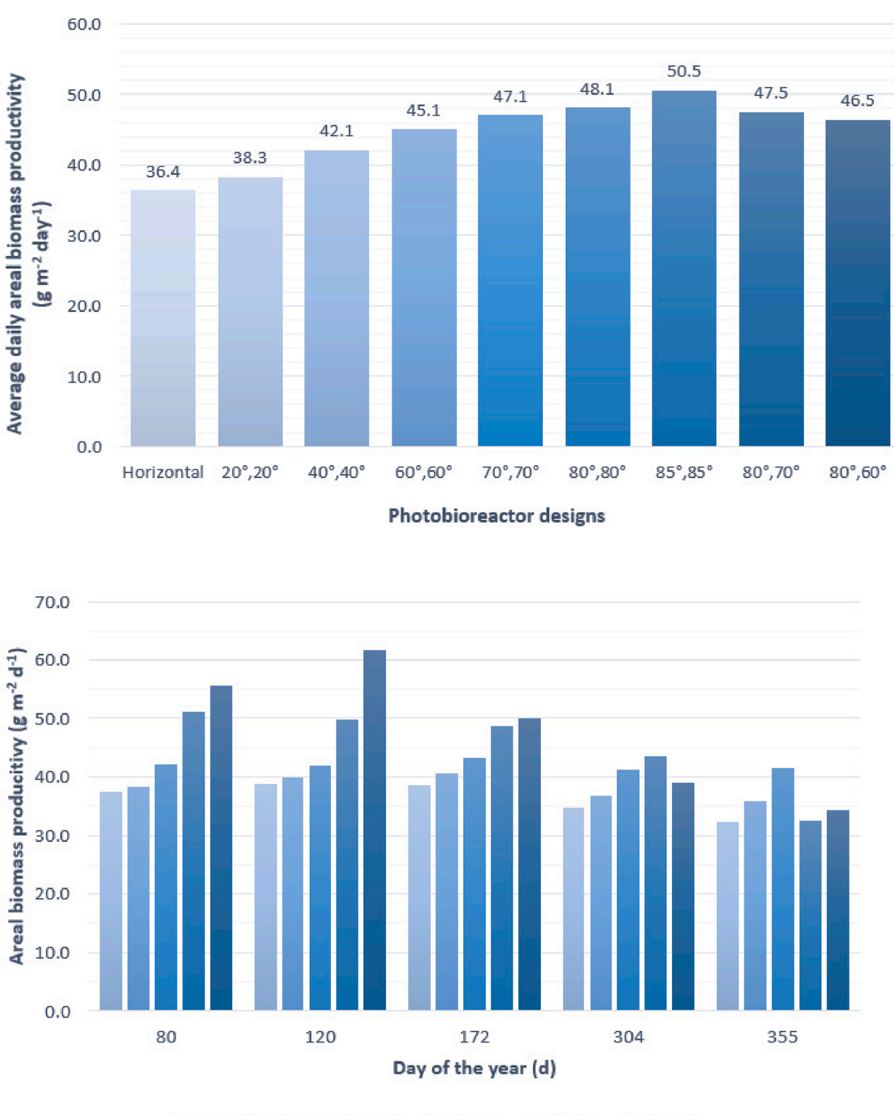
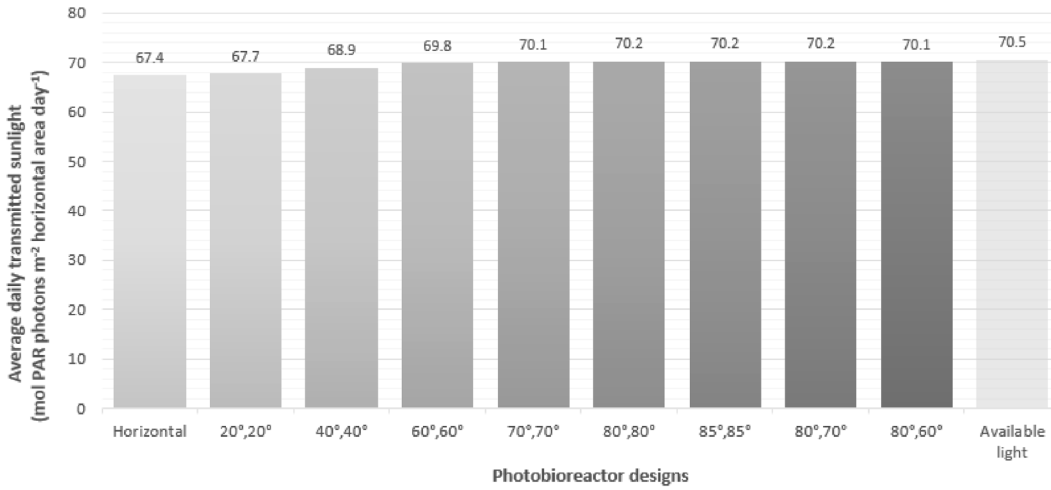


Fig. 5. The average areal biomass productivities of Chlorella sorokiniana on the simulated days in the modelled photobioreactors (top) and the areal biomass productivities in several of the modelled photobioreactors on each of the simulated days (bottom). The designs of the modelled V-shaped photobioreactors differed in the set of inclination angles for the flat panels β_N,β_S. The biomass productivities in the photobioreactors were recalculated to productivities per unit of occupied horizontal surface area to allow direct comparison of the different designs.



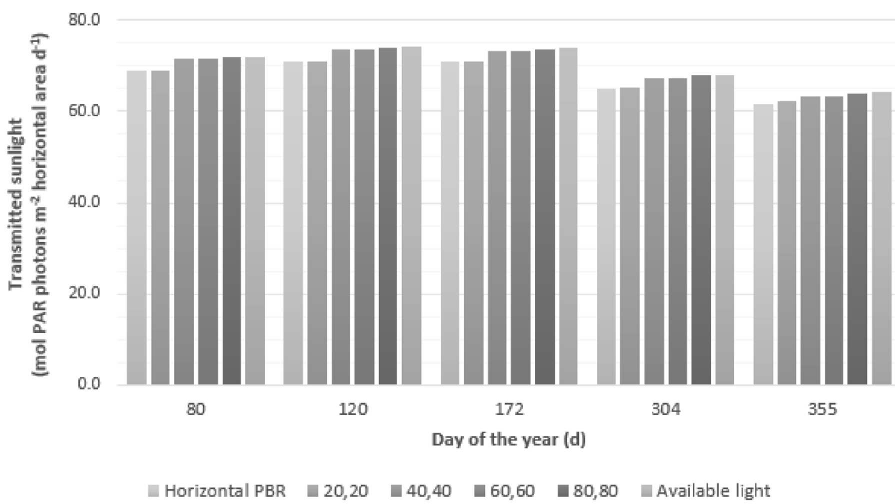


Fig. 6. The average amount of sunlight transmitted into the modelled horizontal and V-shaped photobioreactors on the simulated days (top) and into several of the modelled photobioreactors on each of the simulated days (bottom). The V-shaped photobioreactor designs differed in the inclination angles of the panels β_N,β_S. The sunlight transmitted into the V-shaped photobioreactors was recalculated to the photon flux density on a horizontal surface to allow direct comparison of the different designs.

sunlight reaching the Earth's surface will be lower due to reflection and scattering of light (see section 3.4). Moreover, the differences in light availability between the simulated days are small, amounting to less than 8 mol PAR photons per day, indicating steady availability of sunlight throughout the year. Of the available sunlight, our model showed that on average more than 95% is captured and transmitted into the modelled horizontal and V-shaped photobioreactors (Fig. 6). Thus, less than 5% of the available photons is lost due to reflection at the reactor surfaces. These losses were found to be similar on all simulated days (Fig. 6).

Nonetheless, the model results illustrate that V-shaped photobioreactors capture 0.04 to 4.6% more sunlight than a horizontal photobioreactor (Fig. 6). The higher light capture in V-shaped photobioreactors is the result of light trapping. In V-shaped photobioreactors, light can be reflected multiple times between the reactor panels, depending on the relative position of the sun and the incidence angle of the solar rays, whereas in a horizontal photobioreactor, light is always reflected away from the reactor. Consequently, the reflective losses of light in a horizontal photobioreactor are larger than those in V-shaped photobioreactors; differences of up to 3 mol PAR photons m^{-2} day^{-1} were found (Fig. 6). Moreover, the model results reveal that more light is "trapped" in V-shaped photobioreactor designs with larger panel inclination angles, resulting in a higher light capture. Correspondingly, research on thin-film photovoltaic cells has also shown that light trapping in V-shaped layers increases with decreasing vertex angles between the layers [22].

At the same time, light trapping in the V-shaped photobioreactors was found to reduce reflective losses of sunlight by merely several percent compared to reflective losses in a horizontal photobioreactor (Fig. 6), meaning that the significant gain in biomass productivity in V-shaped photobioreactors compared to a horizontal reactor (Fig. 5) cannot be explained by the relatively small differences in light capture and that light dilution plays a bigger role. In addition, when comparing V-shaped photobioreactors to vertical photobioreactors, it must be noted that in vertical systems, light is additionally lost to the ground in between the units, which can amount to about one-third of the irradiation in large-scale vertical photobioreactors [18]. While these losses of light can be reduced by decreasing the distance between the parallel vertical panels, the biomass productivity also decreases at very short distances due to shadow formation at the bottom of the panels. As a result, less light reaches the lower parts of the reactor, as shown in [28].

3.3. *Improved dilution of sunlight in the V-shaped photobioreactors*

Besides the amount of sunlight captured in a photobioreactor, the intensity at which this light enters the culture also determines the biomass productivity (Fig. 3). In V-shaped photobioreactors, spatial differences can exist in the intensity of the light entering the culture at reactor surface of the panels, since parts of the reactor surface can receive sunlight travelling directly from the sun, parts can receive only reflected light or both, whereas parts can be completely shaded. In addition, the light reaching the reactor surfaces of the panels can enter the culture at different angles. The distribution of sunlight over the reactor surface as well as the incidence angle of the solar changes in time. With our model, the intensity of light entering each reactor section was calculated in time, thereby taking spatial differences into account. Fig. 7 presents the average intensity of the sunlight entering the culture at the glass-culture interface of the photobioreactors during the simulated days. Thus, the figure gives an indication of the intensity of the light entering the reactors, but does not depict the exact light intensities distributed over the reactor.

The results show that the average ingoing light intensities in the V-shaped photobioreactor are much lower than those in the horizontal photobioreactor during most of the day (Fig. 7). On all simulated days,

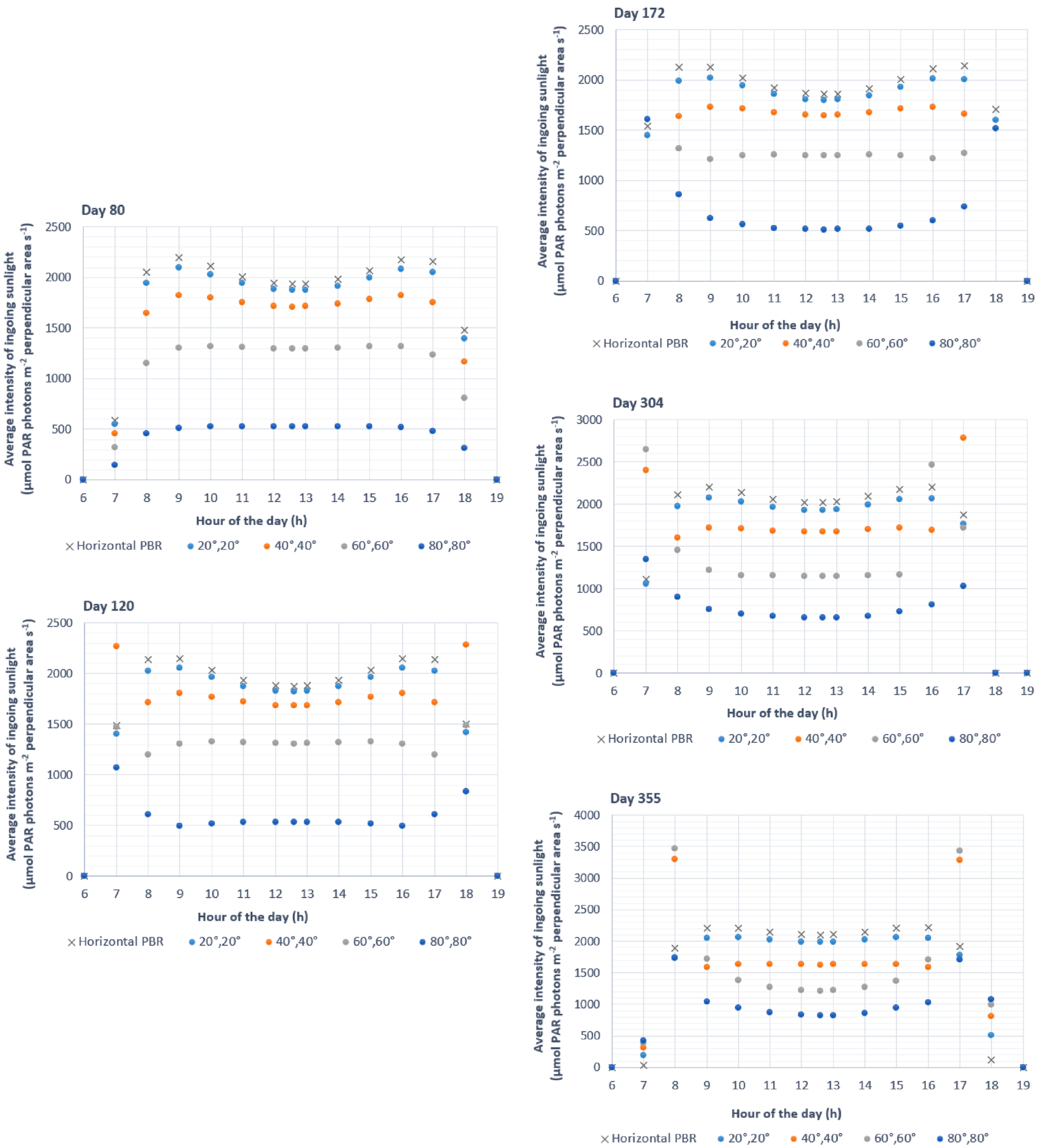


Fig. 7. The average intensity of sunlight entering the modelled photobioreactors on the simulated days (µmol PAR photons m^{-2} perpendicular area s^{-1}). Since spatial differences exist over the reactor surfaces, the values do not depict the exact light intensities distributed over the reactor but give an indication of the intensity of the light transmitted into the reactors.

V-shaped photobioreactor designs allow incident sunlight on Bonaire to be diluted, especially around noon (Fig. 7). Additionally, V-shaped photobioreactor designs with the largest panel inclination angles were found to dilute light to the lowest intensities (Fig. 7). For instance, in the V-shaped photobioreactor with panel inclination angles of 80°, the average ingoing light intensity at noon is much lower than 1000 μmol PAR photons m^{-2} s^{-1}, especially in the summer, whereas in the horizontal photobioreactor the light intensity at noon is around 2000 μmol PAR photons m^{-2} s^{-1} throughout the year (Fig. 7). These results can be explained by the angle of incidence of sunlight onto the reactor panels. The angle of incidence is generally larger around midday, when the sun reaches its highest position in the sky relative to the Earth's surface. Additionally, the angle of incidence around noon also increases the more vertical the reactor panels are. A larger angle of incidence results in a higher degree of refraction and light dilution.

Since the modelled horizontal and V-shaped photobioreactors photobioreactor were found to capture nearly the same amount of light (Fig. 6), the gain in biomass productivity in the modelled V-shaped photobioreactors compared to the horizontal photobioreactor (Fig. 5) is predominantly caused by the dilution of light entering the culture of the reactors. Lower light intensities allow for higher biomass yields on light (Fig. 3). The biomass yield on light specifies the amount of biomass that is produced per mole of photons (g biomass mol^{-1} photons) and can also be expressed as photosynthetic efficiency, which indicates the fraction of light energy that is converted into chemical energy in biomass (Table 2). Among the modelled V-shaped photobioreactors, the daily biomass yield on light and the daily photosynthetic efficiency were found to be highest in the V-shaped designs with the largest panel inclination angles, reaching values of up to 0.74 g biomass mol^{-1} PAR photons and 3.4% (Table 2). Compared to a horizontal photobioreactor, this is a gain of up to 37% in the modelled V-shaped photobioreactors. Thus, V-shaped photobioreactors enable photons to be used more efficiently to produce biomass.

3.4. Implications of model results for microalgae cultivation in V-shaped photobioreactors at low latitudes

Our model results show that V-shaped photobioreactors enable sunlight to be diluted to lower intensities when entering the culture, which reduces the photo-saturation effect and allows for higher biomass yields on light, higher photosynthetic efficiencies, and higher daily areal biomass productivities compared to a horizontal photobioreactor (Table 2 and Fig. 5). For the modelled V-shaped photobioreactors, average daily biomass productivities and photosynthetic efficiencies of up to 50.5 g m^{-2} d^{-1} and 3.3% were estimated, which are about 1.4 times higher than the values estimated for a horizontal photobioreactor. These results are relatively high compared to values reported in literature. For instance, in the Netherlands, maximal areal productivities of 24.4 g m^{-2} d^{-1} and 27.5 g m^{-2} d^{-1} were obtained for *Nannochloropsis* sp. grown in outdoor vertical tubular and flat panel reactors, respectively [9]. Average photosynthetic efficiencies of 2.4% and 2.7% were achieved in those reactors over a 36-day period in the summer [9]. Other studies present similar or lower values [9]. In addition, the estimated volumetric biomass productivities of 0.4–3.6 g L^{-1} d^{-1} in the V-shaped photobioreactors are in a similar range as, or higher than, values reported in literature [6,29,30,9]. It must be noted that the results reported in literature are often not directly comparable to each other, or to the model results in this study, due to differences in light intensities, outdoor temperatures, microalgae strains, reactor dimensions, the time of the year, and other cultivation or operational conditions. In addition, factors including temperature, pH, nutrient supply, mixing, and gas hold-up can also affect the biomass productivity of cultivations systems. These factors were not incorporated into the model, as light-limiting conditions were assumed, and their effect must still be studied in V-shaped photobioreactors. In addition, cell maintenance during the night was not considered in the model, but would result in small biomass losses in practice. The purpose of our model was to investigate and compare the theoretical biomass productivity in different V-shaped photobioreactor designs as a result of light capture and dilution at a low-latitude location. The model results reflect the maximal biomass productivities of *Chlorella sorokiniana* that can be achieved in the modelled photobioreactors under clear-sky conditions and assuming light-limited growth.

Table 2
The average daily biomass yield on lights and photosynthetic efficiencies in the modelled photobioreactors.

Photobioreactor designs	Biomass yield on light [g biomass mol^{-1} PAR photons]	PE, PAR-range [%]	PE, complete sunlight spectrum [%]
Horizontal	0.52	5.6	2.4
20°,20°	0.54	5.9	2.5
40°,40°	0.60	6.4	2.7
60°,60°	0.64	6.9	2.9
70°,70°	0.67	7.2	3.0
80°,80°	0.68	7.4	3.1
85°,85°	0.72	7.7	3.3
80°,70°	0.67	7.3	3.1
80°,60°	0.66	7.1	3.0

Furthermore, while the model results of this study give an indication of potential biomass productivities and photosynthetic efficiencies that can be achieved in V-shaped photobioreactors at low latitudes, they are based on several assumptions. First of all, biological parameters specific for *Chlorella sorokiniana* were used to obtain a function for the biomass yield on light at different light intensities (Fig. 3). The values of these parameters, including the maximal growth rate, the maximal biomass yield on light, the maintenance coefficient, and the absorption cross-section are dependent on the microalgae strain as well as the cultivation conditions, and they determine how efficiently light is used for biomass production. Thus, for other microalgae strains and conditions, the corresponding values need to be obtained and used to estimate biomass productivities in the V-shaped photobioreactors.

Moreover, it was assumed that an optimal biomass concentration is maintained in the photobioreactors, meaning that the amount of light available throughout the culture is sufficient to compensate for maintenance. In practice, this would mean that the biomass concentration varies during the day; the highest biomass concentrations would be reached when the culture is exposed to the highest light intensities, and lower light intensities would correspond with lower concentrations. Still, using the microalgal growth model, it can be seen that the optimal biomass concentrations, based on the average light intensities entering the modelled photobioreactors (Fig. 7), are relatively constant throughout the day (Fig. 8). Hence, in practice the biomass concentration in the photobioreactors can indeed be maintained close to the optimal biomass concentration by controlled reactor dilution. Additionally, it has been found with our photosynthetic growth model that the volumetric productivity of a photobioreactor does not change much over a wide range of biomass concentrations [5]. Other studies also show that the productivity of a photobioreactor does not vary significantly over a two- or three-fold change in concentration [31,32] Thus, it is expected that a wide range of biomass concentrations will result in biomass productivities close to the predicted maximal productivities in our model. Furthermore, it must be noted that in future research on V-shaped photobioreactors, the effect of biomass concentration on downstream processing must be considered. The average biomass concentration in V-shaped photobioreactors decreases with the inclination angles of the panels (Fig. 8), which can ultimately increase the cost of downstream processing of the biomass and the most cost-efficient balance must be determined.

Another assumption in our model simulations is a clear sky, i.e. a cloudless atmosphere. Thus, it is presumed that no scattering of light by water vapor and particles occurs and therefore that all sunlight reaching

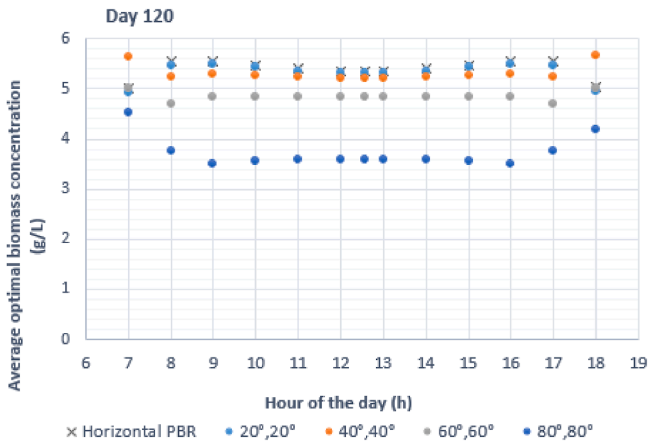


Fig. 8. The optimal biomass concentrations in the modelled photobioreactors on day 120. These concentrations were computed based on the average intensity of sunlight entering the reactors (Fig. 7), using the biological growth model presented in [25].

the photobioreactors is direct, meaning that it travels in a straight line from the Sun to the reactor. This is a simplification, since in reality part of the sunlight reaching the Earth will be diffuse, travelling from all directions. In addition, scattering and reflection of light causes less light to ultimately reach the Earth's surface. In practice, the fraction of diffuse sunlight can change during the day as well as during the year; around noon and in the summer almost all sunlight can be direct, whereas at the beginning and end of the day and in the winter the fraction of diffuse light typically increases [33,34]. At the same time, it must be noted that the fraction of diffuse sunlight is generally much smaller as well as less variable during the year at low latitudes and sunny locations compared to higher latitude and cloudier locations [33]. In this study we focus on and propose a novel photobioreactor design for low-latitude regions, where the ability to dilute intense collimated light can lead to substantial productivity gains. Under these conditions, a V-shaped photobioreactor design is particularly beneficial.

Nevertheless, the inclusion of diffuse sunlight in the model will improve the estimation of the intensity of sunlight entering the photobioreactors and the biomass productivity. Hourly irradiance data provided by global climate database *Meteonorm 8*, which were generated based on measured irradiance over recent decades at a nearby weather station on neighboring island Curacao, shows the variation in direct and diffuse sunlight during the year (Appendix C). Direct irradiation can amount to as much as 90% of all irradiance to as little as 0%, depending on the time of the day and the cloud cover, among others. In addition, the weather data show maximum irradiance levels of 1500–2000 μmol PAR photons m^{-2} s^{-1} at noon on most days. Thus, irradiance levels in the presence of clouds can be up to 25% lower on some days compared to the model results for clear-sky conditions. The lower availability of sunlight and larger fraction of diffuse radiation on overcast days will result in lower biomass productivities; the extent of which will depend on the distribution and intensity of the direct and diffuse light entering the culture. The model presented in this study essentially simulates the highest possible light availability and intensities on Bonaire, and therefore gives an indication of the potential biomass productivities on the sunniest days. While these productivities can be approached on some days, and represent the maximum biomass productivities, they cannot be extrapolated to long periods, as not every day is expected to be characterized by clear-sky conditions in practice. In further research, experimentation is necessary to investigate the productivity of V-shaped photobioreactors under actual outdoor conditions.

4. Conclusions

In conclusion, our model results illustrate that significant gains in biomass productivities and photosynthetic efficiencies can be achieved with V-shaped photobioreactors at low latitude locations. While available sunlight can be captured in these reactors due to light trapping, the productivity gains compared to a horizontal photobioreactor are primarily a result of the dilution of this sunlight to much lower intensities at midday, allowing light to be used more efficiently for biomass production. Increasing the inclination angles of the panels was found to improve light dilution by enabling larger incidence angles of sunlight on the reactor surfaces around noon. At the same time, it must be considered that, with the inclination of the panels, the volumetric productivity decreases, while the complexity of the system, the material use and the reactor costs per area will also increase. Therefore, the gains in areal biomass productivity and photosynthetic efficiency in combination with such challenges, as well as downstream processing, must still be investigated and weighed in future research and application for microalgae cultivation.

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CRediT authorship contribution statement

Rocca C. Chin-On: Conceptualization, Data curation, Methodology, Software, Investigation, Writing – original draft. **Maria J. Barbosa:** Funding acquisition, Supervision, Writing – review & editing. **Rene H. Wijffels:** Funding acquisition, Supervision, Writing – review & editing. **Marcel Janssen:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendices. Supplementary data

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References

[1] R.H. Wijffels, M.J. Barbosa, An outlook on microalgal biofuels, Science 329 (5993) (2010) 796–799.
[2] M.R. Tredici, Photobiology of microalgae mass cultures: understanding the tools for the next green revolution, Biofuels 1 (1) (2010) 143–162.
[3] J. Ruiz, G. Olivieri, J. De Vree, R. Bosma, P. Willems, J.H. Reith, M.H.M. Eppink, D.M.M. Kleinegris, R. Wijffels, M.J. Barbos, Towards industrial products from microalgae, Energy Environ. Sci. 9 (10) (2016) 3036–3045.
[4] R.H. Wijffels, M.J. Barbosa, M.H.M. Eppink, Microalgae for the production of bulk chemicals and biofuels, Biofuels, Bioprod. Biorefin. 4 (3) (2010) 287–295.
[5] M.G.J. Janssen, Microalgal Photosynthesis and Growth in Mass Culture : Chapter Four, in: Advances in Chemical Engineering, 2016, pp. 185–256.

[6] M.R. Tredici, G.C. Zittelli, Efficiency of sunlight utilization: Tubular versus flat photobioreactors, Biotechnol. Bioeng. 57 (2) (1998) 187–197.
[7] A. Richmond, Biological principles of mass cultivation of photoautotrophic microalgae: Chapter 11, in: A. Richmond, Q. Hu (Eds.), Handbook of Microalgal Culture: Applied Phycology and Biotechnology, John Wiley & Sons, 2013, pp. 171–204.
[8] G. Olivieri, L. Gargiulo, P. Lettieri, L. Mazzei, P. Salatino, A. Marzocchella, Photobioreactors for microalgal cultures: A Lagrangian model coupling hydrodynamics and kinetics, Biotechnol. Prog. 31 (5) (2015) 1259–1272.
[9] J.H. de Vree, R. Bosma, M. Janssen, M.J. Barbosa, R.H. Wijffels, Comparison of four outdoor pilot-scale photobioreactors, Biotechnol. Biofuels 8 (2015) 215.
[10] N.G. Schoepp, R.L. Stewart, V. Sun, A.J. Quigley, D. Mendola, S.P. Mayfield, M. D. Burkart, System and method for research-scale outdoor production of microalgae and cyanobacteria, Bioresour. Technol. 166 (2014) 273–281.
[11] L. Rodolfi, G.C. Zittelli, N. Bassi, G. Padovani, N. Biondi, G. Bonini, M.R. Tredici, Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor, Biotechnol. Bioeng. 102 (1) (2008) 100–112.
[12] R. Bosma, M.H. Vermue, J. Tramper, R.H. Wijffels, Towards increased microalgal productivity in photobioreactors, Int. Sugar J. 112 (2010) 74–85.
[13] C.U. Ugwu, H. Aoyagi, H. Uchiyama, Photobioreactors for mass cultivation of algae, Bioresour. Technol. 99 (10) (2008) 4021–4028.
[14] G. Zittelli, N. Biondi, L. Rodolfi and M. R. Tredici, "Photobioreactors for Mass Production of Microalgae: Chapter 13," in *Handbook of Microalgal Culture: Applied Phycology and Biotechnology*, A. Richmond and Q. Hu, Eds., John Wiley & Sons, 2013, pp. 225-266.
[15] J.F. Zijffers, M.G.J. Janssen, J. Tramper, R.H. Wijffels, Design process of an area-efficient photobioreactor, Mar. Biotechnol. 10 (4) (2008) 404–415.
[16] M. Janssen, J. Tramper, L. R. Mur and R. H. Wijffels, "Enclosed outdoor photobioreactors: Light regime, photosynthetic efficiency, scale-up, and future prospects," *Biotechnology and Bioengineering,* vol. 81, no. 2, 2002.
[17] M. Cuaresma, M. Janssen, C. Vilchez, R.H. Wijffels, Horizontal or vertical photobioreactors? How to improve microalgae photosynthetic efficiency, Bioresour. Technol. 102 (2011) 5129–5137.
[18] C.H. Endres, A. Roth, T.B. Bruck, Modeling microalgae productivity in industrial-scale vertical flat panel photobioreactors, Environ. Sci. Technol. 52 (9) (2018) 5490–5498.
[19] Z. Tang, W. Tress, O. Inganas, Light trapping in thin film organic solar cells, Mater. Today 17 (8) (2014) 389–396.
[20] S.J. Kim, G.Y. Margulis, S. Rim, M.L. Brongersma, M.D. McGehee, P. Peumans, Geometric light trapping with a V-trap for efficient organic solar cells, Opt. Express 21 (53) (2013) A305–A312.
[21] C. Cho, H. Kim, S. Jeong, S. Baek, J. Seo, D. Han, K. Kim, Y. Park, S. Yoo, J. Lee, Random and V-groove texturing for efficient light trapping in organic photovoltaic cells, Sol. Energy Mater. Sol. Cells 115 (2013) 36–41.
[22] C. Cho and J. Lee, "Multi-scale and angular analysis of ray-optical light trapping schemes in thin-film solar cells: Micro lens array, V-shaped configuration, and double parabolic trapper," *Optics Express,* vol. 21, no. S2, pp. A276-A284, 2013.
[23] C. Cho, K. Nam, Y. H. Seo, K. Kim, Y. Park, J. Han and J. Lee, "Study of optical configurations for multiple enhancement of microalgal biomass production," *Scientific Reports,* vol. 9, no. 1723, 2019.
[24] MathWorks, *MATLAB,* Natick.
[25] W. Blanken, P.R. Postma, L. de Winter, R.H. Wijffels, M. Janssen, Predicting microalgae growth, Algal Res. 14 (2016) 28–38.
[26] T. de Mooij, K. Schediwy, R.H. Wijffels, M. Janssen, Modeling the competition between antenna size mutant and wild type microalgae in outdoor mass culture, J. Biotechnol. 240 (2016) 1–13.
[27] H. Takache, G. Christophe, J.F. Cornet, J. Pruvost, Experimental and theoretical assessment of maximum productivities for the microalgae Chlamydomonas reinhardtii in two different geometries of photobioreactors, Biotechnol. Prog. 26 (2) (2010) 431–440.
[28] P.M. Slegers, R.H. Wijffels, G. van Straten, A.J.B. van Boxtel, Design scenarios for flat panel photobioreactors, Appl. Energy 88 (2011) 3342–3353.
[29] M.H.A. Michels, P.M. Slegers, M.H. Vermue, R.H. Wijffels, Effect of biomass concentration on the productivity of Tetraselmis suecica in a pilot-scale tubular photobioreactor using natural sunlight, Algal Res. 4 (2014) 12–18.
[30] A. San Pedro, C.V. Gonzalez-Lopez, F.G. Acien, E. Molina-Grima, Outdoor pilot-scale production of Nannochloropsis gaditana: Influence of culture parameters and lipid production rates in tubular photobioreactors, Bioresour. Technol. 169 (2014) 667–676.
[31] J.H. de Vree, R. Bosma, R. Wieggers, S. Gegic, M. Janssen, M.J. Barbosa, R. H. Wijffels, Turbidostat operation of outdoor pilot-scale photobioreactors, Algal Research 18 (2016) 198–208.
[32] K. Tuantet, H. Temmink, G. Zeeman, R.H. Wijffels, C.J.N. Buisman, M. Janssen, Optimization of algae production on urine, Algae Res. 44 (2019), 101667.
[33] A. Zangvil, O.E. Aviv, On the effect of latitude and season on the relation between the diffuse fraction of solar radiation and the ratio of global to extraterrestrial radiation, Sol. Energy 39 (4) (1987) 321–327.
[34] C.J.T. Spitters, H.A.J.M. Toussaint, J. Goudriaan, Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis Part I. Components of incoming radiation, Agric. For. Meteorol. 38 (1–3) (1986) 217–229.