Feasibility Study on Combined Production of Algae and Tomatoes in a Dutch Greenhouse

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Abstract

The Dutch horticultural sector shows interest in production of microalgae. When microalgae and a tomato crop are produced in the same greenhouse, both shared advantage of and competition for resources will occur. In this study a model was developed to predict algae biomass production in tubular photobioreactors (PBR) and to assess the economic feasibility of combined production of tomatoes and algae. The effects of the location of the PBR in the greenhouse, the diameter of the PBR tubes, the algae biomass concentration, the light intensity and the PBR temperature were considered. The economic feasibility of combined production was calculated, taking into account both investment and running costs. Three possible locations for the PBRs were considered. The most sensitive growth factor influencing economics of the systems was light. Economic feasibility of algae production underneath the tomato crop was poor; a minimum unit biomass production cost of 70 € kg^{-1} dry matter (DM) was calculated. Increasing the light intensity by decrease of the tomato LAI through extra leaf picking increases economic feasibility of algae production underneath the crop. Economic feasibility of algae production in a separated compartment was computed to be good with a minimum unit biomass production cost of 11 € kg^{-1} DM. The developed model can function as a basis for further research on combined production of a crop and microalgae in Dutch greenhouses.

INTRODUCTION

The on-going quest for non-fossil based chemicals and fuels strongly renewed interest in microalgae during the last two decades (Luque, 2010; Norsker et al., 2011). Microalgae are a large and very diverse group of organisms. Becker (1994) and Barbosa (2003) indicate that microalgae could be produced as a source for a large number of applications, including (health) food, feed, pharmaceutics, cosmetics, pigments, chemicals, fuel, biomass, hormones, bio-fertiliser and for waste water treatment.

The Dutch horticultural sector has shown interest in production of algae. Pressure on economic margins and drive for innovation makes growers interested in alternative ways to exploit their resources and capital. The resources needed for production of vegetable crops and algae are comparable, for optimal growth both need a controlled climate, proper light conditions, dissolved nutrients, carbon dioxide, space and management. Integration of the two cultivations could be an interesting option to increase efficient utilization of resources. At the same time, competition for resources, especially light, will occur. Little is known about the best location, type, or dimension of the photobioreactor (PBR) to be used. Neither is there much knowledge about the potential productivity and related costs and returns of algae production systems at large scale, especially when production takes place in a greenhouse or in combination with a crop.

The objective of this study was to determine the productivity and economic feasibility of combined production of tomatoes and algae in a Dutch greenhouse. A model was developed to determine the influence of a number of parameters and system characteristics on algal productivity and on the costs and returns of the complete system.

Algal growth rate was modelled with temperature and light as variables. Other parameters influencing the growth rate were assumed to be optimal or non-limiting.

METHODS

The following sections first describe the modelled system, then the parameters and system characteristics which were varied for the scenario analysis and finally the main equations and parameters of the developed model will be detailed.

System Description

The main parts of the modelled system are the greenhouse system, the tomato crop, the PBR system and the algae culture. A typical Venlo-type greenhouse was considered with a total production area of 1 ha. The width of the greenhouse was divided in 13 sections of 8 m, each of them containing 5 crop rows. A crop row was divided in space for growing the crop (crop gutter, 1 m width) and a path for logistics and work done in the crop (0.6 m width). The tomato crop was assumed to be grown according to state of the art practice in Dutch horticulture, with the production cycle running from 15 December of the year to 15 November the next year. The gutters on which the crop is grown are mounted approximately 0.80 m above the floor, leaving space underneath where PBR tubes can be placed. The dimensions of the PBR system were derived from a system currently implemented by a tomato grower and were modified and scaled up according to the greenhouse set-up proposed above. A horizontal tubular reactor system was modelled and three tube diameters, 0.06, 0.11 and 0.16 m, could be implemented. Two main options for combining production of algae and tomatoes in one greenhouse were considered, termed “Integrated production” and “Separated production”.

1. Integrated Production. In Integrated production, PBR tubes were modelled parallel to the crop row. They could be placed either underneath the crop or on the path or both under the crop and on the path. As in the system implemented by one Dutch grower, six pipes per row were placed under the crop for a tube diameter of 0.06 m, four for a diameter of 0.11 m and two for a diameter of 0.16 m. This resulted in PBR systems with a volume of respectively 107, 238 and 252 m^3. Every loop of the PBR had a length of 192 m (two times the effective length of the greenhouse). An increased length of the PBR loop increases the risk of oxygen inhibition. For a PBR with a diameter of 0.06 m, a biomass concentration of 2 kg/m^3 and a liquid velocity of 0.5 m/s, van Beveren (2011) calculates a maximum tube length of 125 m in full light conditions on 5 May 2009, assuming 300% air saturation of oxygen to be the upper level to avoid inhibition. In “Integrated Production”, the light intensity at the PBR-level is rather low, allowing for the longer tube length.

2. Separated Production. When algae are produced underneath a tomato crop, the availability of light strongly limits the productivity of the PBR. Therefore the direct link between tomato and algae production was uncoupled by placing them in different compartments. The same greenhouse dimensions were used, but the number of rows used for tomato production was adapted according to the calculated space needed to fit a certain number of PBR tubes. The distance between the tubes was taken to be equal to one third of the tube diameter, in order to largely avoid self-shading of the PBRs. Light intensity in “Separated production” is much higher compared to “Integrated production”, therefore the length of a PBR loop is decreased to 96 m.

Scenario Analysis

Algae production in combination with tomato production is a new concept. Little is known about the effects of changing the system set-up or the potential of different systems, both in view of productivity and economics. Therefore it is useful to determine a number of parameters which are expected to influence productivity and economic feasibility the most. In this study, scenarios were set up by varying or modifying the following parameters related to light conditions: the location and diameter of the PBR, the leaf area index (LAI) of the tomato crop and the biomass concentration in the PBR.

Model

A fully deterministic, MatLab®-based model was developed, which can be used to analyse scenarios regarding the productivity and economics of combined production of algae and tomatoes. The model itself consists of three main parts, a greenhouse climate model, an algae production model and an economic analysis model. The core of the model is an algae growth model, which determines the algal growth rate on the basis of PBR temperature and light conditions.

1. Greenhouse Climate Model. With the extensive dynamic simulation model KASPRO, the physical parameters regarding the greenhouse environment, the crop photosynthesis and dry matter production of a tomato crop and the energy balance were simulated on an hourly basis (Zwart, 1996). A replica of a commercially available greenhouse controller is integrated in KASPRO, therefore it can be assumed that the PBRs were influenced by the greenhouse climate, but that influence of the PBRs on the greenhouse climate was compensated by the climate controller. For "Separated production" it was assumed that the climate in the compartment with tomatoes was completely isolated from the climate in the second compartment with algae. For both compartments a separate KASPRO simulation was executed.

2. Algae Production Model. An increasing number of algal growth rate models are available and described in literature (Zonneveld, 1998; Thornton et al., 2010). Virtually all models are based on lab-scale experiments. In the current study, an empirical model was chosen which describes the growth of the red alga *Porphyridium cruentum*, influenced by temperature and radiation. As described by Dermoun et al. (1992), temperature and light are certainly two of the main factors acting on overall biomass productivity in algal mass-culture systems. Non-limited nutrient conditions, non-limiting O_2 and CO_2 concentrations, ideal pH and a perfectly mixed system were assumed. KASPRO-output data regarding radiation, greenhouse air temperature and LAI of the tomato crop were used as input to the algae production model. These data were modified to obtain hourly values for radiation incident on the PBR and temperature inside the PBR.

In "Integrated production", radiation passes through the crop canopy before it reaches the PBR. The light incident on the PBR is therefore related to the LAI of the tomato crop. Measurements have been done by Kempkes (unpublished data) for the light extinction in a full grown tomato crop with a LAI of 3. In the crop the amount of radiation at floor level was found to be around 5% of the radiation above the crop, while in the path this was around 20%. No crop was present above the PBR in the "Separated production" case. Therefore it was assumed that 100% of the radiation 'above the crop' reaches the PBR. The PBR wall consists of polyethylene, which reflects 15% of the radiation incident on the bioreactor surface. For calculation of the light conditions inside the PBR, it was decided to use a volumetric averaged light intensity, which was calculated based on the solar radiation incident on the PBR surface and the light path through the PBR (Quinn et al., 2011). This method is based on the assumption that the algae are adapted to this averaged light intensity.

In "Integrated production" it was assumed that the temperature of the PBR always equals the temperature of the greenhouse air as determined by KASPRO, because virtually no direct radiation reaches the PBR and also the total amount of radiation is rather low, so that the influence of solar radiation on the bioreactor temperature is small. In "Separated production", the PBR is subject to full solar radiation. In this case the PBR temperature will deviate from the greenhouse air temperature and it is not acceptable to assume them equal. Therefore the bioreactor temperature was separately modelled following Béchet et al. (2010). Biomass harvesting was assumed to be done with a centrifuge. A lower and upper limit of 1 and 3 kg/m^3 respectively were set for the biomass concentration. When the upper limit was reached, biomass was harvested until the lower limit was reached.

3. Economic Analysis Model. For calculation of the costs and returns of the greenhouse tomato production, both fixed and variable costs and returns were obtained from the KWIN report (Vermeulen, 2010). This report contains all sort of information related to average production, costs of products, labour and other production resources and budget calculations for the Dutch horticultural sector (Vermeulen, 2010). The budget calculation for production of truss tomatoes in combination with a combined heat and power system (CHP) was used. The number of pumps and total pump capacity needed was specifically calculated for all systems.

Norsker et al. (2011) performed an in-depth study on the fixed and variable costs of algae production plants. Data from this study were used and adapted to the systems examined in this study. Fixed costs of the equipment and variable costs have been corrected with help of a volume ratio, which expresses the volume of the systems in relation to the volume of the system studied by Norsker et al. (2011). For “Separated production”, two modifications were done in calculating the costs. Firstly, the minimum liquid velocity was doubled, to prevent oxygen inhibition of the algae. Secondly, fixed costs of the greenhouse construction, ground heating and other greenhouse equipment, were added to algae production for every m^2 of greenhouse occupied, while in “Integrated production”, these costs were completely added to the costs for tomato production.

There is a wide range of products for which algae can be used. The use of the produced algae therefore strongly determines the specific price which can be obtained. In the current study a price of 50 € kg^{-1} DM was used in calculations.

RESULTS

Algal Productivity

Volumetric productivity in kg DM m^{-3} $year^{-1}$ is a measure for the light use efficiency of the PBR, increasing with decreasing PBR tube diameter and with increasing available radiation. Areal productivity in kg DM m^{-2} $year^{-1}$ indicates how effective the floor area is used for algae production. On the path, volumetric productivity was approximately 3 times higher than underneath the crop. Volumetric productivity was approximately 11 and 4 times higher in “Separated production” compared to production under the crop and on the path respectively. Volumetric productivity was approximately 1.4 and 2.3 times higher in the PBR with a tube diameter of 0.06 m compared to the PBR with tube diameter of 0.11 and 0.16 m respectively. Maximum volumetric productivity occurred in the PBR with a diameter of 0.06 m, in “Separated production”, reaching a value of 146.7 kg DM m^{-3} $year^{-1}$. Areal productivity in kg DM m^{-2} in “Integrated production” was highest in the PBR with 0.11 m diameter, due to the high reactor volume per area with a moderate volumetric productivity. Underneath the crop the areal productivity was 0.19 kg DM m^{-2} $year^{-1}$ and on the path 0.29 kg DM m^{-2} $year^{-1}$. In “Separated production”, areal productivity increased with increasing tube diameter. Maximum volumetric productivity was 6.46 kg DM m^{-3} $year^{-1}$ in the PBR with 0.16 m diameter. Figure 1 displays the weekly sum (mole photon m^{-2} $week^{-1}$) of average radiation in the PBR, for two tube diameters and three PBR locations. Figure 2 displays the related weekly sum (kg DM m^{-3} $week^{-1}$) of volumetric productivity.

Decreasing the LAI through extra leaf picking positively affected productivity in “Integrated production”. Effects were strongest for production underneath the crop. When the LAI was decreased with 5%, the volumetric productivity increased on average with 52% and when LAI was decreased with 10%, the average increase in productivity was 110%. For PBRs on the path this was 12 and 26% respectively.

Economic Results

In “Integrated production”, with an assumed price of 50 € kg^{-1} algal DM, profit on algae production is most-times negative and sometimes slightly positive. Increasing PBR tube diameter decreases profit. Profit over the whole integrated system was always negative, the PBR with 0.16 m diameter being least profitable. Reducing the LAI by leaf picking increased the profit, due to increased productivity. Positive total profit was reached when PBRs were implemented both under the crop and on the path, in combination with reduction of the LAI of 5 and 10%. But no extra costs were taken into account for increased labour need. Profit in “Separated production” was related to the scale of the system. Large scale systems resulted in large profits per m^2 greenhouse area. Profit for the PBR with 0.06 m diameter was lower compared to the PBR with 0.11 and 0.16 m diameter. The latter had comparable profit. Unit biomass production costs per kg DM for “Separated production” were lowest for the PBR with 0.06 m diameter and highest for the PBR with 0.16 m diameter, ranging from approximately 11 to 15 € kg^{-1} DM. Fixed costs comprised between 64 and 80% of the total cost of algae DM. Within the fixed costs, the pumps take a large share. The share of energy costs on total costs was very small. The price of algal DM was assumed to be 50 € kg^{-1}, but this price is very dependent on the purpose of the algal DM and will probably change in the future as well. Therefore the influence of varying this price was tested. Figure 3 shows how the price of algal DM influenced the profit on the whole system for algae production under the crop, on the path and in “Separated production”.

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

For “Integrated production”, 95% of the light entering the greenhouse was assumed to reach the PBR when LAI was 0. When LAI was maximum (LAI=3), the radiation intensity on the PBR under the crop and on the path was 5 and 20% of the intensity above the crop respectively, as measured by Kempkes (unpublished data). With these minimum and maxima, the amount of radiation incident on the PBRs was assumed to be linearly related to the LAI of the tomato crop. In practice this relation is not linear, therefore radiation incident on the PBR may be over- or underestimated for the hours when LAI is unequal to zero or to three. The deviation from a linear relation will probably not be very large, and the amount of hours that the LAI is unequal to zero or to three is limited. So the influence of this assumption on the results is expected to be small. It was assumed that all tubes on the same location received the same amount of light, while in practice there will be a difference in the amount of radiation received by the tubes placed under the outer side of the crop compared to the tubes in the middle. It is unknown how large these differences are and what the effect would be on productivity.

In the current study, light intensity in the PBR was approached by calculating an average radiation resulting in equal light intensity for the algae, no matter their location in the PBR. In a real situation, light intensity is dependent on the location in the PBR, which may result in both light limited and light inhibited states of algae in one PBR. Especially for larger tube diameters and under low or high light conditions, an overestimation of productivity is to be expected when the average light method is used.

Tittel et al. (2005) indicate that it is typical for phototrophically grown algae that they exhibit negative growth rates due to maintenance respiration, when light intensities are below the compensation point. In the used algal growth rate model of Dermoun et al. (1992) negative growth never occurs, which is unrealistic. Especially under low-light conditions in “Integrated production”, productivity of the PBR will thus be overestimated. Besides that, the model of Dermoun et al. (1992) was specifically developed for the algal species *Porphyridium Cruentum*. Every algal species has its own growth characteristics, which means that this model certainly is not representative for all algae species. It can be representative though for algal species with comparable temperature needs and maximum growth rate. In this study, algae production was modelled dependent on temperature and radiation only, assuming that nutrient, CO_2 and O_2 concentrations and pH were optimal or non-limiting. In practice this will not be the case and therefore productivity is probably overestimated in this study.

Based on this desktop study it was concluded that combined production of tomato and algae might be economically feasible. Sharing of facilities and resources is the main advantage. Due to a better light use, separated production performs better than integrated production.

This study exists of a desk-study only. Experiments and measurements are planned to be carried out in the future. Results in the study here are reflected with literature data and practical experience of growers only.

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Figures

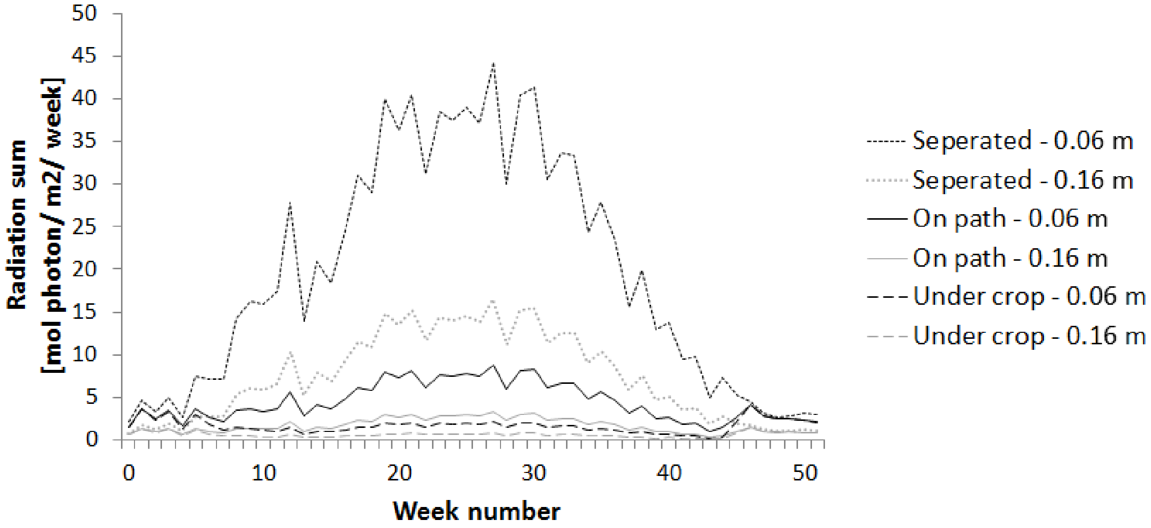

Fig. 1. Weekly sum of average radiation in the PBR, calculated for two tube diameters in "Integrated production" (under crop and on path) and "Separated production".

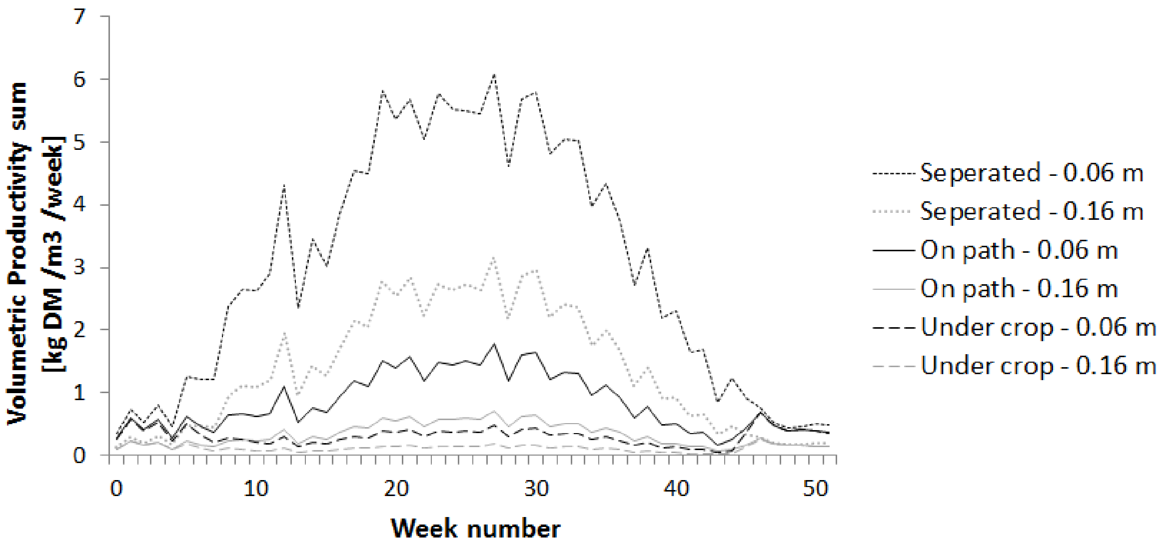

Fig. 2. Weekly sum of volumetric productivity in the PBR, calculated for two tube diameters in "Integrated production" and "Separated production".

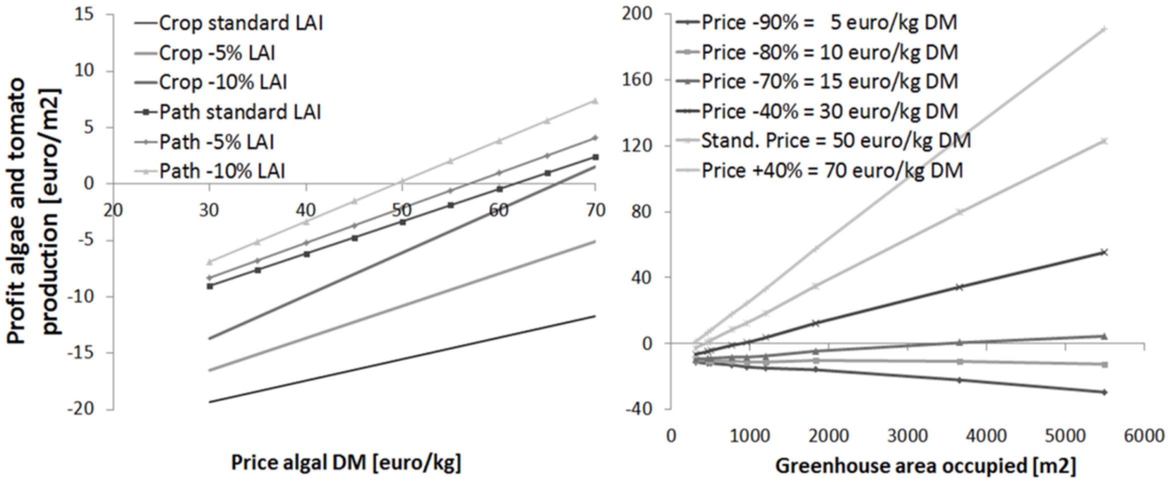

Fig. 3. The effect of varying the price of algae on the overall profit for production of tomatoes and algae in “Integrated production” (left) and in “Separated production”.