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Research Paper

Modelling and evaluation of productivity and economic feasibility of a combined production of tomato and algae in Dutch greenhouses

Bart Slager [a,b], *Athanasios A. Sapounas* [a], *Eldert J. van Henten* [a,b,*],
Silke Hemming [a]

[a] *Wageningen University and Research Centre, Greenhouse Horticulture, Droevendaalsesteeg 1,
6708 PB Wageningen, The Netherlands*
[b] *Wageningen University and Research Centre, Farm Technology Group, Droevendaalsesteeg 1,
6708 PB Wageningen, The Netherlands*

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Combination of production of algae and tomato increases efficient use of available resources of greenhouse enterprises, such as controlled environment, water and nutrients, carbon dioxide, greenhouse space and infrastructure and knowledge. No information is available, however, about the potential productivity and related costs of a combined tomato and algae production in Dutch greenhouses. The objective was to determine the algae productivity in tubular photobioreactors (PBRs) and the economic feasibility of combined production of tomato and algae in Dutch greenhouses. A model was developed to predict greenhouse climate from outside climate, to predict tomato and algae biomass production and to analyse scenarios of different locations and dimensions of tubular PBR in the greenhouse with regard to algae productivity and cost price of algae production. The results show that algal productivity is low if PBRs are installed under a tomato crop due to limited light levels. Areal algal productivity was calculated to be 5–6.5 kg DM m^{-2} if PBRs are installed in a separate greenhouse compartment next to tomato. In this case the minimum cost prices of algae production was calculated to be €11 kg^{-1} DM algae, which give perspectives for the future. The proposed model is important because it gives insight into the feasibility of algae and tomato production in Dutch greenhouses. This novel model approach and the scenario results provide better knowledge about the potential productivity and related costs and returns of algae production in greenhouses.

1. Introduction

The quest for non-fossil based chemicals and fuels has strongly renewed research interest in algae during the last two decades (Luque, 2010; Norsker, Barbosa, Vermuë, & Wijffels, 2011). Algae are a potential resource for food, feed, pharmaceutics, cosmetics, pigments, chemicals, fuel, bio-fertilisers and they can be used for waste water treatment (Becker, 1994; Barbosa, 2003). Between 8000 and 10,000 tons of

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[*] *Corresponding author*. Wageningen University and Research Centre, Greenhouse Horticulture, Droevendaalsesteeg 1, 6708 PB Wageningen, The Netherlands.
E-mail addresses: eldert.vanhenten@12move.nl, eldert.vanhenten@wur.nl (E.J. van Henten).
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Nomenclature

English symbols

C_b	Concentration of algae biomass in PBR kg m^{-3}
C_p	Specific heat capacity of the algae fluid J kg^{-1}
DM	Algae dry matter production m^2 m^{-2}
dt	Integration time step 1 s
d_{tube}	Diameter of the PBR tube m
g_{max}	Maximum algae growth rate at temperature T h^{-1}
L	Length of the PBR tube m
LAI	Leaf area index of tomato crop m^2 m^{-2}
h	Heat transfer coefficient 10 W m^{-2} K^{-1}
I_{av}	Average intensity of PAR inside the PBR μmol m^{-2} s^{-1}
I_{in}	Intensity of total solar radiation inside the greenhouse above Tomato crop W m^{-2}
I_0	Intensity of PAR incident on PBR μmol m^{-2} s^{-1}
I_{opt}	Optimum radiation received by the algae at temperature T h^{-1}
$Q_{ra,sol}$	Radiation flux reaching the PBR directly μmol m^{-2} s^{-1}
$Q_{re,sol}$	Radiation flux reaching the PBR after reflection from the Greenhouse floor μmol m^{-2} s^{-1}
Q_c	Convective energy exchange between PBR and greenhouse air W
r_g	Reflexivity of the greenhouse floor surface 0.5 [–]
T	Temperature K or °C
t	Time 1 h
V	Volume of the PBR system m^3
W_p	Electrical pump power kW

Greek symbols

α	Light absorption coefficient of the algae biomass 0.0752 m^2 g^{-1}
β_I	Shape factor for limitation by radiation 0.50 [–]
β_T^g	Shape factor for limitation of algae growth rate by temperature 0.02 [–]
β_T^I	Shape factor for limitation by I_{opt}0.56 [–]
γ	Maximum growth rate at optimal temperature 0.0583 h^{-1}
ΔP_{total}	Total pressure differences in the PBR system Pa
ε	Emissivity of algae liquid 0.97 [–]
η_p	Efficiency of pump 0.80 [–]
η_m	Efficiency of electric engine driving the pump 0.90 [–]
θ_0^g	Temperature at which algae growth rate is zero 4.7 °C
θ_{opt}^g	Temperature at which algae growth rate is maximum 20.5 °C
θ_0^I	Temperature at which I_{opt} is zero 4.7 °C
θ_{opt}^I	Temperature at which I_{opt} is maximum 12.3 °C
ρ	Density of the algae fluid kg m^{-3}
ρ_I	Maximum radiation flux value at the optimum temperature 538 μmol m^{-2} s^{-1}
τ_{wall}	Transmittance of the polyethylene PBR wall 0.85 [–]
φ_v	Volume flux through PBR tubes m^3 h^{-1}

Subscripts

PBR	Related to the photobioreactor
Air	Related to the greenhouse air
Crop	Related to PBR under crop
Path	Related to PBR on path

microalgae biomass are produced annually, having a market value of approximately \$3000–4000 million (Tredici, Biondi, Ponis, Rodolfi, & Zittelli, 2009).

The Dutch horticultural sector has shown interest in the production of algae. Pressure on economic margins and drive for innovation have triggered the interest of Dutch growers to exploit their resources and capital in a more effective way. The resources needed for production of vegetable crops and algae are quite comparable. Both need light and a properly controlled carbon dioxide concentration (CO_2), nutrient concentrations and temperature for optimal production. Also similarities exist when it comes to required infrastructure, management and knowledge. Essentially, with all technology present and the knowledge and expertise of growers on resource management and optimised biomass production (Dieleman & Hemming, 2011), Dutch greenhouses should be able to facilitate both tomato and algae production effectively. The proposed combined cultivation fits in a wider range of recent developments, in which combinations of different agricultural activities have been studied or attempted. The combination of tomato and fish production, for example, was found to have distinct mutual advantages (Graber & Junge, 2009; Nichols & Savidov, 2012; Rakocy, 2012; Vergote & Vermeulen, 2012).

Currently, several Dutch growers combine the production of tomato with algae in small scale experiments on a very intuitive basis. A more systematic study of integrated production of vegetable crops and algae in Dutch greenhouses is still lacking and quite a range of questions are still unanswered. For instance, Wijffels, Barbosa, and Eppink (2010) estimated that 40–80 t algae dry matter could be produced in closed photobioreactors (PBRs) outdoors, but potential productivity in a greenhouse is yet unknown. The design of a tubular PBR has been studied by several authors (Acién Fernández, García Camacho, Sánchez Pérez, Fernández Sevilla, & Molina Grima, 1997, 1998; Bosma, Van Zessen, Reith, Tramper, & Wijffels, 2007; Molina, Fernández, Acién, & Chisti, 2001; Slegers, van Beveren, Wijffels, Van Straten, & Van Boxtel, 2013), but no design has been studied for greenhouse conditions. The best location of an algae production system in relation to a tomato production system, the suitable dimensions of PBRs and influence of system scale are still unknown.

Integration of the production of vegetable crops and algae does not only increase efficient utilisation of resources, but might also increase competition for resources, especially light. In view of light availability, the dimension as well as the location of algae PBRs in a combined production system has to