A dynamic model simulating the symbiotic effects in aquaponic systems

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Abstract

A dynamic simulation model for a closed-loop aquaponic system was designed based on biological and physical sub-models of both the greenhouse cultivation system and the aquaculture system. The complete model exists mainly of two components: (1) a complete greenhouse climate simulator including the cropping system and (2) the aquaculture system including recirculation system, PVC-containers and others for fish production. The fish cultivation system was calibrated for two systems of 600 and 1000 m² greenhouse system with 700 or 3000 kg peak biomass of tilapia fish (*Oreochromis niloticus*) production. For validation and test, the model system was built in small scale at the site of Copenhagen University, Denmark, i.e. a greenhouse compartment of 100 m² with three fish ponds dimensioned to the size needed for crop irrigation using a combination of leafy vegetables and herbs, and two varieties of fish, i.e. pike perch (*Sander lucioperca*) and tilapia. The modelled combined system was implemented in a greenhouse simulator environment (The Virtual Greenhouse). Simulation studies where performed with the full model using tomato crop and a variation of fish cultures; i.e. the aquaculture ponds were set to a range of constant water temperatures for separate scenario studies, increasing with 2°C from 14 to 34°C. A standard Venlo type shelter of 1000 m² was used for that. The aquaculture system was dimensioned to the crops need of nutrients such that it produces 9 Mt tilapia fish yearly of which a peak system biomass content of 3t fish system^{-1} was calculated. The fish feed was given to the optimum and the minimum intake capacity of fresh water at 12°C was calculated from transpiration and evaporation losses, as other water was recycled in the closed system. Simulation results indicate that greenhouse climate is influenced through the aquaculture system with increased humidity levels and decreased use of energy for heating and CO_2 supply. The amount of energy saving for greenhouse heating increases with fish pond water temperature, while due to the metabolic activity inside the aquaculture system energy consumption for heating the water increased only little in that range. Total energy saving (energy for greenhouse heating and the aquaponics system) increases almost linear with increased pond temperature with 41 MJ m^{-2} K^{-1} year^{-1}. The developed model is useful for planning aquaponic systems and can be used as input model for predictive climate control in greenhouses with combined aquaculture production.

Keywords: crop growth model, DSS, greenhouse climate, model, perch, simulation, software, tilapia

INTRODUCTION

Aquaponic systems are recirculating aquaculture systems that incorporate the production of plants without soil while commonly leafy vegetables as lettuce production is combined with bulk fish as cat fish or tilapia (Sikawa and Yakupitiyage, 2010). The systems are rather new with first publication of the mid-70s (i.e. Sneed et al., 1975; Naegel, 1977) and after slow development commercially interesting activities are growing with more

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knowledge in this field (Love et al., 2015). When integrating horticulture with aquaculture production the benefits of various symbiotic effects will occur (Graber and Junge, 2009). These are: a) metabolic bi-products from the fish production are utilized by the horticultural plants to grow and hence clean the water as well as save cost on plant fertilizer; b) fish produce CO_2, which the plants can utilize hence reduce cost on purchasing CO_2 to boost plant production; c) the fish tanks, when placed in the greenhouse for horticultural produce, can act as heating buffers during night time and hence save cost on energy consumption. One of the few drawbacks though is the higher humidity level in the greenhouse air through a higher evaporation from the aquaculture tanks. Within the young niche field of aquaponics (Love et al., 2015) research was mainly focused on nutrient household while only few studies focused on modelling the symbiotic effect while incorporating energy fluxes (Sikawa and Yakupitiyage, 2010).

In order to evaluate, analyse and optimize the system thoroughly, the complex system of a greenhouse including macro- and microclimate calculations from a vast amount of possible system layouts as modelled earlier and summarised in the decision support tool *The Virtual Greenhouse* (Körner and Hansen, 2012) was combined with a here developed model of the aquaculture system as additional module for system definition. The strength of this combined model tool is the detailed deterministic approach of both the greenhouse and the aquaculture system and their modelled interactions, enabling the analysis of the different components and sub-components. As such, in this study the symbiotic effects have been modeled to quantify their physical environmental impact and their interactions.

MATERIALS AND METHODS

Model

The aquaponic system was calibrated on production data with peak biomass of 700 kg within the system (AkvaGroup, Denmark). The fish feed was given to the optimum with a peak feed capacity of 20 kg day^{-1} and a peak water exchange of 0.3 m^3 h^{-1} and minimum intake capacity of fresh water was calculated from transpiration and evaporation losses. Additionally, the needed water supply for keeping the desired water temperature at minimum of 28°C and a maximum of 32°C was calculated from fresh water supply at pre-heated water. The model consists mainly of 6 components:

- Determination of container-wall temperature for heat exchange;
- Heat exchange with greenhouse air and aquaculture containers by convection, conduction and radiative processes;
- Heat exchange with container water and container wall by convection and conduction;
- Latent heat production from the aquaculture containers;
- CO_2 production of the fish;
- CO_2 production of biological break-down.

1. Container heat-transmission.

Heat exchange (ϕ, J m^{-2} s^{-1}) between the aquaculture system and the greenhouse environment is modelled with heat balance of the involved components as e.g. conductive heat flux through the aquaculture container wall (ϕ_{wall}), convection between outer or inner container surfaces and air or water ($\phi_{s,a}$ or $\phi_{s,w}$, respectively), and radiative heat exchange between wall surface and the greenhouse ($\phi_{s,gh}$) (see Equations 1-4). The temperatures of inside and outside wall surfaces ($T_{wall,i}$ or $T_{wall,o}$) is determined from energy balance (see Figure 1).

$$\phi_{wall} = {d_{wall}}^{-1}\, k_{wall}\, (T_{wall,o} - T_{wall,i}) \quad (1)$$

$$\phi_{s,a} = K_{wall,a}\, (T_a - T_{wall,o}) \quad (2)$$

$$\phi_{s,w} = K_{wall,w} (T_w - T_{wall,i}) \quad (3)$$

$$\phi_{s,gh} = \varepsilon \, \sigma \, (T_{wall,o}{}^4 - T_{gh}{}^4) \quad (4)$$

with defined wall diameter ($d_{wall,}$ m), thermal conductivity of the wall material (k_{wall}, J m^{-1} s^{-1} K^{-1}), and the convective heat coefficients for container wall surface to air water and water ($K_{wall,a}$, $K_{wall,w}$, J m^{-2} s^{-1} K^{-1}).

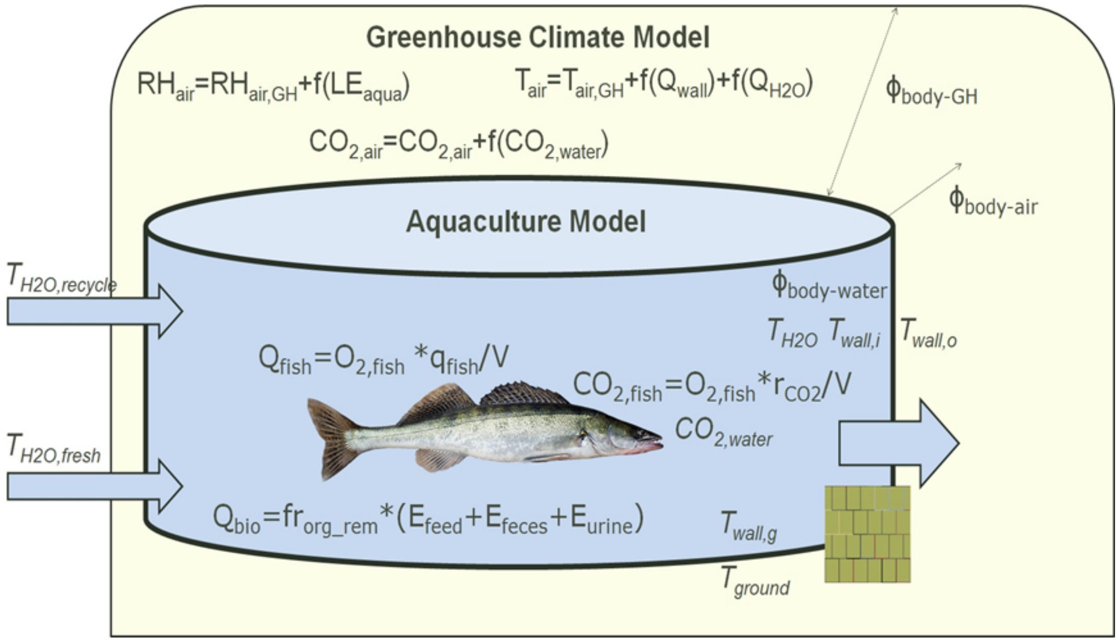

Figure 1. Graphical figure of one unit of the aquaculture system implemented in the greenhouse with humidity, temperature and CO_2 concentrations of the air (RH_{air} T_{air}, $CO_{2,air}$), heat from (Q) fish environment (fish), biological breakdown (bio) and heat fluxes ϕ).

2. Heat production aquaculture.

The fish culture produces heat through metabolic processes. The amount of heat produced by the fishes (Q_{fish}) is directly calculated from O_2 consumption that is a function of temperature (see Equation 5) and a constant for heat production for one unit oxygen consumed (*φ,* i.e. 13608 J g^{-1} (Eding et al., 2000)).

$$Q_{fish} = O_{2,aqua} \, \varphi \quad (5)$$

Heat from breakdown of organic matter (Q_{bio}) as e.g. feces and feed remains are contributing to the heat balance. Energy supply to the water system was calculated by heat production through the fish calculated from an average oxygen consumption rate (f_{O2}) of 0.48 kg kg^{-1} feed with 13608 J g^{-1} feed. A rate of 51% of oxygen waste was assumed.

Additional heat production was calculated by biological break-down of feces (1.3 MJ kg^{-1} feed) and feed. Feed composition was 40% protein, 10% fat and 20% carbohydrates. Feed conversion was 1, the rates of energy conversion of remaining feed used for biological breakdown were 23.64, 39.54 and 17.15 MJ g^{-1} for protein, fat and carbohydrates, respectively.

3. Latent heat production.

Amount of evaporation (E_{aqua}, kg m^{-2} s^{-1}) and absolute humidity from the aquaculture units to the greenhouse was handled similar to crop evaporation as calculated from ambient humidity (X_a, kg m^{-3}), transpiration conductance (g_{tr}, m s^{-1}), and the effective humidity of the open surface of the aquaculture system ($X_{eff,aqua}$), calculated from saturated vapour (X_{sat}, kg m^{-3}), the density of air (ρ_a, kg m^{-3}), psychrometric constant (γ), boundary layer resistance of the water surface ($r_{b,aqua}$, s m^{-1}) fraction of open aquaponics systems (θ), the heat of vaporisation of water (L, J kg^{-1}), and absorbed short wave radiation ($R_{n,a,aqua}$, J m^{-2} s^{-1})

$$E_{aqua} = g_{tr}(X_{eff,aqua} - X_a) \quad (6)$$

$$X_{eff,aqua} = X_{sat} + \frac{\rho_a}{\gamma}\frac{r_{b,aqua}}{\theta}\frac{R_{n,a,aqua}}{L} \quad (7)$$

4. CO_2 production fish.

The fish produces CO_2 through respiration as function of temperature. The CO_2 is supplied to the greenhouse air via transport and temperature functions. Oxygen consumption rate (f_{O2}) was estimated to 0.48 kg O_2 kg^{-1} feed while oxygen delivery was at 28°C calculated to 0.4 kg h^{-1}, thus the calculations using feed amount (f_{fish}), fraction of feed loss (w_{O2}), water temperature (T_w) and mass balance of O_2/CO_2 in order to calculate CO_2 delivery to the environment (Equations 8 and 9).

$$O_{2,T_{w,b}} = f_{fish} \times f_{O_{2,T_{w,b}}} \times w_{O_2} \quad (8)$$

$$CO_{2,aqua} = \frac{[CO_2]}{[O_2]} O_{2,T_{w,b}} \times Q_{10,R}{}^{(T_w - T_{w,b})/10} \quad (9)$$

with oxygen delivery to the system at a given water temperature at water base temperature $T_{w,b}$, and the Q_{10} value of fish respiration ($Q_{10,R}$).

Simulations

Yearround simulation were performed with the core of *The Virtual Greenhouse*™, (Körner and Hansen, 2012) that consists of a compilation of physical and biological greenhouse simulation models. For that, a model system of an aquaponic system was created and connected to the greenhouse simulator. An aquaponic system dimensioned to produce 9 Mt fish year^{-1} of a total system volume of 65 m^3 separated in 6 circular tanks of each 10 m^3 plus system components as pipes etc. of 5 m^3 water capacity were placed under benches in a 1.000 m^2 *Venlo-type* greenhouse (4 m gutter heights).

A recirculation system was used where aquaculture water was cleaned with filters and made available for crop irrigation. Used water by the crop was calculated from transpiration loss and the difference was supplied as fresh water with a temperature of 12°C temperature.

The greenhouse was a standard greenhouse type with tomato cultivation in gutters with stonewool substrate. The greenhouse was equipped with an energy screen and a shading screen (LS16 or ILS60 Revolux, respectively, Ludvig Svensson, Sweden) under the roof and equipped with standard heating pipe system and passive roof vents. Climate control was done according to common practice with installed supplementary lighting of 80 Wm^{-2} (HPSL 400 W, Philips, The Netherlands) and sufficient dosage capacity of pure CO_2.

Temperature setpoints for tomato cultivation was set to 18 and 20°C year round. No distinguish between seasons, day and night and cultivation stage was done for model simplification. CO_2 was dosed to a maximum of 800 ppm at daytime, but supply stopped when vents were opened with more than 10%.

For simulations, the Danish reference climate year (Lund, 1995) with hourly data was used as input. Simulations were done with a 5-min time step over a complete year. Two main set-ups were simulated: 1) The greenhouse without aquaponic system using regular tomato cultivation (same climate setpoints as with aquaponics) and 2) the greenhouse with the combined 6-tank aquaponic system installed under the crop. For this latter case, scenarios were created with different water temperature set points increasing with 2°C for each scenario from 14 to 34°C.

RESULTS AND DISCUSSION

The energy content of the pond water within the model was dynamically influenced by several external variables as biomass heat production, heat exchange with the greenhouse, evaporation, and fresh water supply. The interfaces between greenhouse- and aquaculture system were the inside and outside surfaces of the container-pond walls for heat exchange (inside and outside wall temperatures were modelled with conductive heat exchange), the top-open container for evaporation and CO_2 exchange from fish-pond to the greenhouse, and the pond-water used for fertigation and irrigation of the crop, such that crop transpiration resulted in a need of fresh water supply to the fish-pond.

Energy content of the aquaculture system, i.e. temperature, of the water was influenced by metabolic activity of the fish, the biological break down of fish-feed composition and feces, convective heat exchange between inside pond-wall, while greenhouse energy content was influenced by evaporative water from the open aqua-system and convective heat energy exchange with the outside pond-container wall.

Simulation scenarios show when integrating horticultural production with aquaculture the benefits of various symbiotic effects will occur as metabolic bi-products from fish production are utilized by the horticultural crop, fish produce CO_2, which plants utilize at daytime; and the fish tanks within the greenhouse act as heating buffers and hence save cost on energy. Depending on the set points, the total energy consumption for greenhouse heating was reduced when the aquaponics water system temperature was in average higher than the greenhouse temperature set point (Figures 2 and 3; Table 1). With cool fish cultures below 20°C cultivation temperature, greenhouse energy consumption increases due to the cold body inside. However, also with lower temperatures of the aquaculture systems, CO_2 supply can be reduced. A slight increase of crop yield to a max of 1.8% was observed. This was mainly due to a higher CO_2 level in the greenhouses with aquaponics.

Compared to tomato culture without aquaponics systems, total energy saving (energy for greenhouse heating and the aquaponics system) increases almost linear with increased pond temperature with 41 MJ m^{-2} K^{-1} $year^{-1}$ (see Figure 3A).

Energy saving for the greenhouse environment is due to the heat capacity of the aquaponics system that acts as a heating source and buffer. Thus, the higher the pond temperature, the more heating is saved for the crop system. However, a higher pond temperature set point uses a higher amount of heating for the aqua-system. Taking both energy sources for heating of the aqua-system and the greenhouse into account, still results in net energy saving as it can be seen from in Table 1. Processes by metabolic activities in the aquaponic system provide energy to the water that in turn reduces the heating demand.

Table 1. Heat energy and CO_2 supply saving in % with an aquaponics system compared to the same greenhouse without aquaponics, using tomato crop.

	% saving										
	Water set point (°C)										
	14	16	18	20	22	24	26	28	30	32	34
Heat energy[1]	-9.9	-7.1	-3.8	-0.8	2.9	6.7	11.5	16.6	22.0	27.2	33.1
Heat energy[2]	-10.3	-7.9	-5.2	-2.7	0.4	3.4	7.3	11.4	15.6	19.4	23.8
CO_2 supply	5.2	6.2	7.2	8.1	7.7	9.6	9.8	12.3	14.1	16.6	18.9

[1]Energy of the greenhouse only.

[2]Greenhouse and aquaponics energy combined (heating).

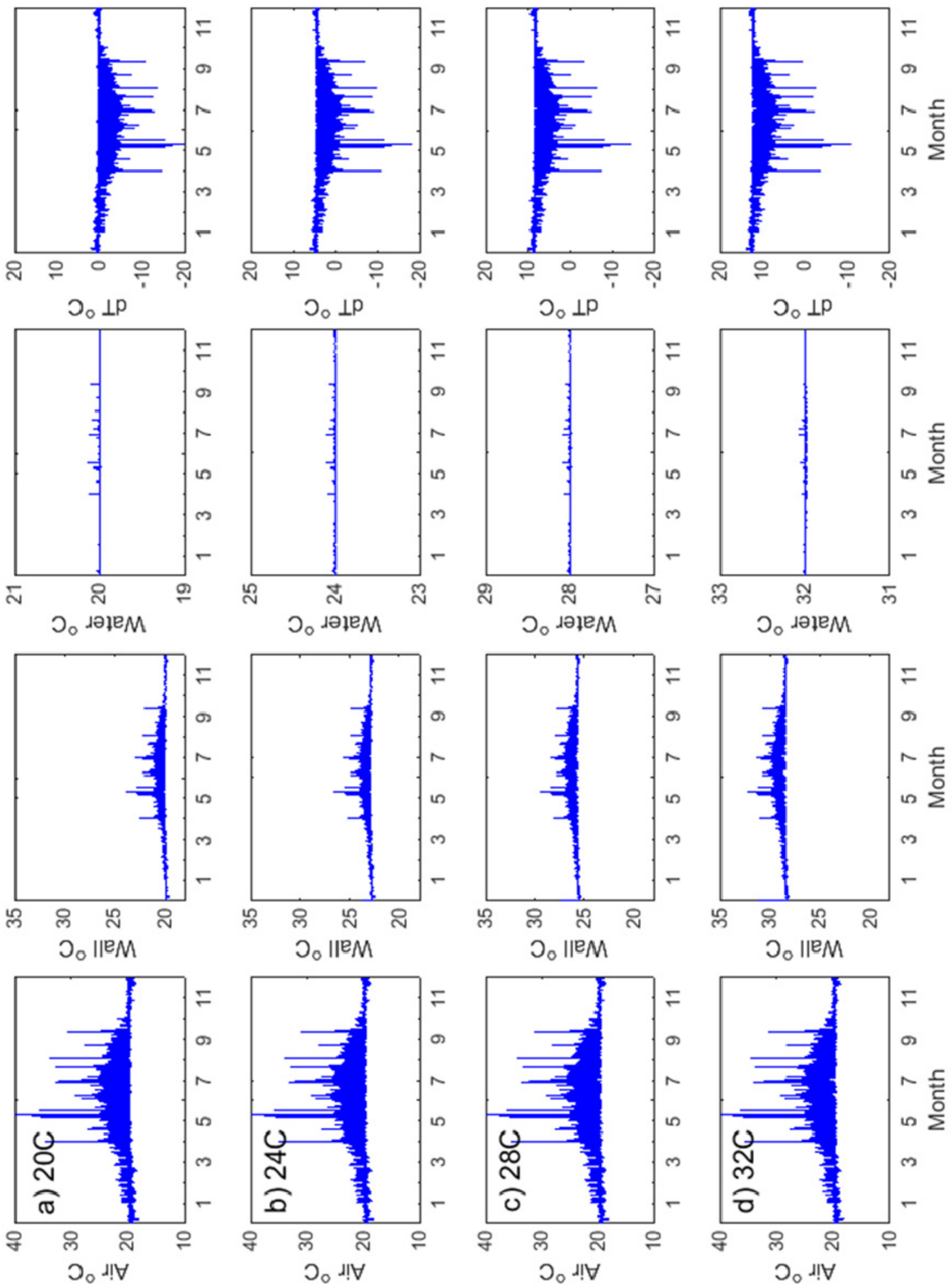

Figure 2. Hourly plots of 1-year simulation results of key variables as greenhouse air temperature (air), average outer wall temperature (wall), water temperature (water) and the difference between outer wall temperature and air temperature (dT), data are plotted with different scales.

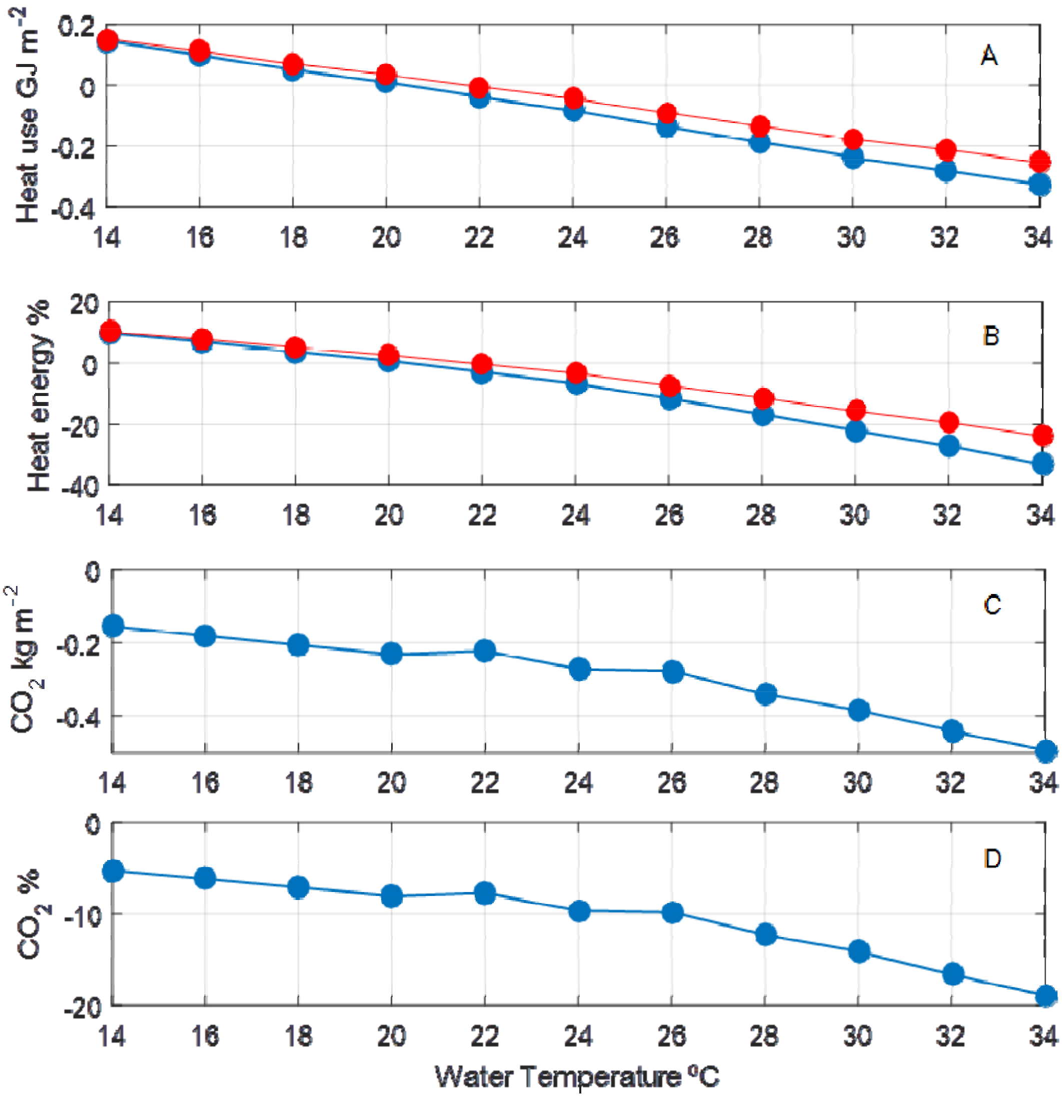

Figure 3. Differences between greenhouse with and without aquaponics system as simulated greenhouse energy consumption (A, B) without energy for the aquasystem (blue) and with energy for the aqua-system (red), and CO_2 supply (C, D).

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