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Oxygen consumption in recirculating nutrient film technique in aquaponics

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ABSTRACT

Due to root respiration, a minimum oxygen concentration in the root zone of plants is necessary. To keep the plant healthy and fully efficient the concentration should not fall below a plant specific critical value. Especially in nutrient film technique, the oxygen concentration can deplete heavily during the daytime. Besides the root respiration also microorganisms, living in the root zone of the plants, consume oxygen and have to be considered. In double recirculating aquaponic systems (DRAPS) fish waste water is used for preparation of nutrient solution for plant production in hydroponics. The fish waste water, delivered by a recirculating aquaculture system (RAS), probably contains high amounts of microorganism which can compete with plants for oxygen.

The present study was conducted to investigate the oxygen concentration of nutrient solutions used in both, conventional hydroponics and in DRAPS, respectively. Therefore, the oxygen concentration within the cultivation trenches of conventional hydroponics (control; nutrient solution prepared with fresh water, electrical conductivity (EC) 1.8 dS m^{-1}) and DRAPS (nutrient solution prepared with fish waste water (AP), EC 1.8 dS m^{-1} (low) and EC 3.0 dS m^{-1} (high)) were investigated. To evaluate whether the differences in oxygen depletion might be almost due to the used process water, the oxygen consumption of the prepared nutrient solutions was investigated separately without plants.

The oxygen concentration within the cultivation trenches followed a typical daily fluctuation pattern with a decreasing oxygen concentration during the day. As time passed from April to June the depletion during the day increased and was strongest in AP high. In June the oxygen concentration dropped partly to zero in AP high, while it dropped only to nearly 150 µmol L^{-1} and 60 µmol L^{-1} in control and AP low, respectively. The oxygen consumption of pure nutrient solution (without plants) was significantly different between AP high and control, which also affects the oxygen concentration within the cultivation trenches.

1. Introduction

Due to their energy demanding physiological activities (Morard and Silvestre, 1996) plant roots show a high respiration rate and therefore a high oxygen demand (Nielsen et al., 1998). According to Morard and Silvestre (1996) the root respiration depends on plant species and can differ from 1.44 µmol O_2 h^{-1} g^{-1} fresh matter (FM) to 7.8 µmol O_2 h^{-1} g^{-1} FM. The oxygen concentration in the nutrient solution can have an effect on plant performance in various forms (Bradford and Hsiao, 1982; Gislerød and Kempton, 1983; Morard et al., 2000; Morard

Abbreviations: 3-cp, 3-chamber-pit; AP, aquaponics; DRAPS, double recirculating aquaponics; EC, electrical conductivity; FM, fresh matter; NFT, nutrient film technique; O_2, oxygen; $O_{2,a}$, actual oxygen concentrations; $O_{2,amb}$, air oxygen concentration; $O_{2,cons}$, oxygen consumption; $O_{2,e}$, oxygen concentration in the efflux; $O_{2,i}$, oxygen concentration in the influx; $O_{2,m}$, measured oxygen concentration; $O_{2,sat,t}$, maximal oxygen concentration at given temperature; $O_{2,t0}$, oxygen concentration at the beginning of the measurement (full saturated); $O_{2,t370}$, oxygen concentration after 370 min/at the end of the measurement; PAR, photosynthetically active radiation; PPFD, photosynthetic photon flux density (PPFD); Q, flow rate; r, Pearson correlation coefficients; RAS, recirculating aquaculture system; V, volume

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and Silvestre, 1996; Stępniewski and Przywara, 1992) and is an important factor for plant growth. As such, a long term depletion of oxygen can lead to reduced plant growth and finally to declined yields (Gislerød and Kempton, 1983; Morard and Silvestre, 1996). A reason for growth depression can be a reduced water uptake by plants. It has been shown that the water uptake of tomatoes was reduced by 20%–30% after 48 h of oxygen depletion (Morard et al., 2000). This reduced uptake of water can cause stomatal closure and thus reduced transpiration (Bradford and Hsiao, 1982). However, not only the uptake of water but also the uptake of essential nutrients decreases due to oxygen deficiency (Stępniewski and Przywara, 1992). In terms of potassium, even an efflux from the roots into the environment was detected at low oxygen concentrations (Morard et al., 2000; Morard and Silvestre, 1996). Besides that, a good oxygen supply is also necessary for plant health. It was reported that a high oxygen concentration (11%–14%) prevented plants from infection with *Pythium* F707, while lower oxygen concentrations (5.8%–7% and 0.8%–1.5%) in the nutrient solution increased infection rate (Chérif et al., 1997).

In nutient film technique (NFT) the roots are permanently surrounded by flowing nutrient solution, which appears as a barrier to gaseous exchange. However, in soilless culture systems oxygen deficiency mostly does not affect the complete root system, but specific parts are frequently affected. Even if only specific root parts are affected by oxygen depletion, it can cause a disturbance of the functioning of the root as described above (Morard and Silvestre, 1996). Gislerød and Kempton (1983) found in NFT trenches with cucumber an increasing depletion of oxygen from the inlet to the outlet. While the concentration was uncritical near the inlet (6.2 mg L^{-1}/193.8 µmol L^{-1}), it dropped to critical values for cucumber downstream at the last plant (2.9 mg L^{-1}/90.6 µmol L^{-1}). However, the depletion along the cultivation trenches was less when tomatoes were cultivated (decrease from 8.3 mg L^{-1} to 7.5 mg L^{-1}/259.4 µmol L^{-1} to 234.46 µmol L^{-1}). In contrast, the investigations of Holtman et al. (2009a) showed that the oxygen concentration in other NFT cultivation trenches for tomatoes can decrease to below 1 mg L^{-1} (31.3 µmol L^{-1}) during daytime in spring. This is below the critical value of 4 mg L^{-1} (≙ 125 µmol L^{-1}) for tomatoes (Zeroni et al., 1983). In deep water hydroponic systems, for example, oxygen supply to the plant root is the main problem (Zeroni et al., 1983).

The oxygen concentration in aqueous solutions, such as nutrient solutions used in horticulture, depends on different parameters. As such, the solubility of oxygen in aqueous solutions itself is affected. For instance, an increasing salt concentration (MacArthur, 1916) or a raising temperature (Carpenter, 1966) reduces the solubility of oxygen. In addition, oxygen concentration in nutrient solutions is affected also by biological factors. Plants withdraw oxygen due to respiration, and microorganisms in the nutrient solution and in the root zone consume oxygen as well (Jackson, 1980; Strayer, 1994). For conventional hydroponic systems, municipal/tap water, well water or ditch water, partly mixed with rain water, are used to prepare the nutrient solutions (Stanghellini and Kempkes, 2004). The amount of microorganisms and the number of species vary within the different water sources, and are usually low in well water (Strayer, 1994). For double recirculating aquaponic systems (DRAPS) fish waste water from recirculating aquaculture systems (RAS) is used to prepare the nutrient solution (Suhl et al., 2016). The RAS system contains a biofilter where microorganisms convert ammonium to nitrate (Tyson et al., 2011). Therefore, it can be expected that fish waste water from RAS contains much more and different microorganisms (Strayer, 1994; Sugita et al., 2005) than well water. Additionally, total suspended solids (TSS) accumulating in RAS and are a major source of carbonaceous oxygen demand (Timmons et al., 2010). This implies that the competition for oxygen between plants, microorganisms, and TSS is likely much higher in DRAPS than in conventional hydroponics, prepared with well water. DRAPS are developed for intensive fish and plant production (Kloas et al., 2015; Suhl et al., 2016). For intensive plant production optimal conditions, including oxygen concentration and gas exchange in the root zone, are essential and its assurance was the motivation for this study.

During an annual investigation of tomato production in a conventional hydroponics system and DRAPS the oxygen concentration in the nutrient solution was observed. The nutrient solutions of the different treatments were prepared with well water and mineral fertilizer for conventional hydroponic on the one hand and with fish waste water and mineral fertilizer for aquaponics on the other hand. To evaluate the different oxygen concentrations within the nutrient solutions while passing the root zone, the oxygen consumption within the trenches was calculated. To get information about the impact of the plant activity a correlation analysis were done for the oxygen concentration within the trenches and the photosynthetically active radiation. The main focus of the present study was, to investigate if the nutrient solutions (prepared with well water or fish waste water) itself (without plants) differed in the oxygen concentration and to understand how strong this effect was. This information is necessary to understand hydroponics under DRAPS conditions and, if necessary to give recommendations to adjust and to improve the conditions for optimal plant growth, comparable to conventional hydroponic conditions.

2. Materials and methods

The construction and design of the used double recirculating aquaponic system (DRAPS) is in detail described by Suhl et al. (2016) and pictured in Fig. 1. The investigations took part in a Venlo-type greenhouse of a DRAPS (hydroponic, Fig. 1) during the annual tomato production in 2015. The fish rearing (Nile tilapia; *Oreochromis niloticus*) is described in detail by Suhl et al. (2016). The hydroponic unit is described below, in paragraph 2.1. The recirculating aquaculture system (RAS) and the hydroponic unit are connected via a sedimentation unit, a storage tank and a preparing station to adjust the used fish waste water by adding mineral fertilizer and acid. The sedimentation unit consists of the mechanical sedimentation filter, as part of the RAS, and the 3-chamber-pit (3-cp). To perform the daily needed water exchange in the RAS, the fish water was released from the mechanical filter into the 3-cp to separate the sludge from the fish waste water. After the fish waste water passed the three chambers passively, it was pumped into a storage tank within the greenhouse where it was stored until its use as nutrient solution for plant irrigation. The sludge was separated within the 1st chamber of the 3-cp. The 2nd chamber was ventilated and the 3rd chamber was used as reservoir to pump the water into the storage tank.

2.1. Plant production

From February until April 2015 the set-points for the heating system in the greenhouse were set to 22 °C and 18 °C (day, night). To cool the greenhouse the ventilation opened at 26 °C. From mid-April the set-points for the heating system were reduced to 17 °C (day, night) and the ventilation opened already at 21 °C. The energy screen opened stepwise one hour before sunrise and closed from one hour after sunset. The artificial light started at a level below 20 W m^{-2} global radiations between 7 a.m. and 8 p.m.

In the greenhouse two single trenches and three double trenches where installed (Fig. 2) at a net-acreage of 82.7 m^2. The single trenches were placed at the left and right outer wall of the greenhouse, respectively, and were not considered for experiments. In total 192 tomato plants (*Solanum lycopersicum* L., cv. Pureza) were cultivated and grew in the recirculating nutrient film technique (NFT) system. In each 13 m long trench a total number of 24 plants were planted. This resulted in a plant density of 2.3 plants m^{-2} in the greenhouse. The nutrient solution was constantly pumped from the nutrient solution tank to the end of each trench and circulated back in a free gradient (slope 1%) at a flow rate of 9 L min^{-1}. The plants were planted at 22nd January with about eleven leaves and when the 1st trusses were already visible.

Three different treatments with two trenches each were applied. Per

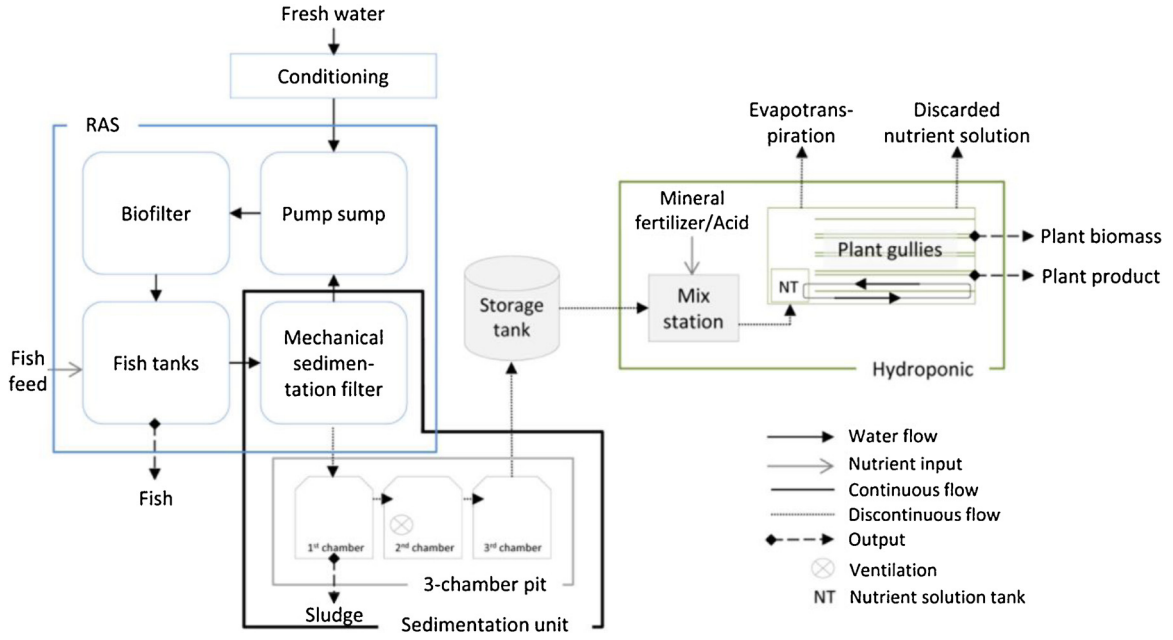

Fig. 1. Schematic flow of the investigated double recirculating aquaponic system (DRAPS) according to Suhl et al. (2018b). The blue lines comprise the recirculating aquaculture system (RAS) and the green lines mark the hydroponic unit used for investigations. The RAS and hydroponic unit were connected via a sedimentation unit consisting of a mechanical sedimentation filter and a 3-chamber-pit, a storage tank, and the preparing station to adjust the fish waste water using mineral fertilizer and acid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

treatment 48 plants were cultivated in two trenches. For the various treatments the nutrient solutions were prepared with different process waters. For the control treatment, the nutrient solutions were prepared with fresh water and for the two aquaponic treatments the nutrient solutions were prepared with fish waste water. To prepare the nutrient solution for the control, mineral fertilizer was added up to an electrical conductivity (EC) level of 1.8 dS m^{-1}. In case of the aquaponic treatments, the nutrient solutions were adjusted with mineral fertilizer to an EC level of 1.8 dS m^{-1} (hereinafter referred to as AP low) for the one treatment, and for the other treatment to an EC level of 3.0 dS m^{-1} (hereinafter referred to as AP high). The fish waste water was delivered from the associated recirculating aquaculture system, rearing Nile tilapia. For preparation of the nutrient solution an automatic mixing station controlled by EC and pH was used, as exactly described by Suhl et al. (2018b).

The use of fish waste water to prepare the nutrient solution started at 05.02.2015. To provide an optimal nutrient concentration in the nutrient solution, the fresh water for the control and the fish waste water for the aquaponic treatments were analysed periodically. The target nutrient concentration was composed according to Lattauschke (2004) as following: 151 mg L^{-1} nitrogen (N), 37 mg L^{-1} phosphorus (P), 234 mg L^{-1} potassium (K), 128 mg L^{-1} calcium (Ca), 24 mg L^{-1} magnesium (Mg), 110 mg L^{-1} sulphur (S), 2.0 mg L^{-1} iron (Fe), 0.3 mg L^{-1} boron (B), 0.2 mg L^{-1} copper (Cu), 1.2 mg L^{-1} manganese (Mn), 0.05 mg L^{-1} molybdenum (Mo) and 0.4 mg L^{-1} zinc (Zn). The pH was adjusted to 5.8 using phosphoric acid. The corresponding EC level for this target nutrient concentration was EC 1.8 dS m^{-1} and this was applied to the control and AP low solutions. To reach EC 3.0 dS m^{-1} respectively higher concentrations were contained.

2.2. Measurement of photosynthetic photon flux density

To measure the photosynthetic photon flux density (PPFD) in µmol m^{-2} s^{-1} two PAR (photosynthetic active radiation) sensors (type LI-

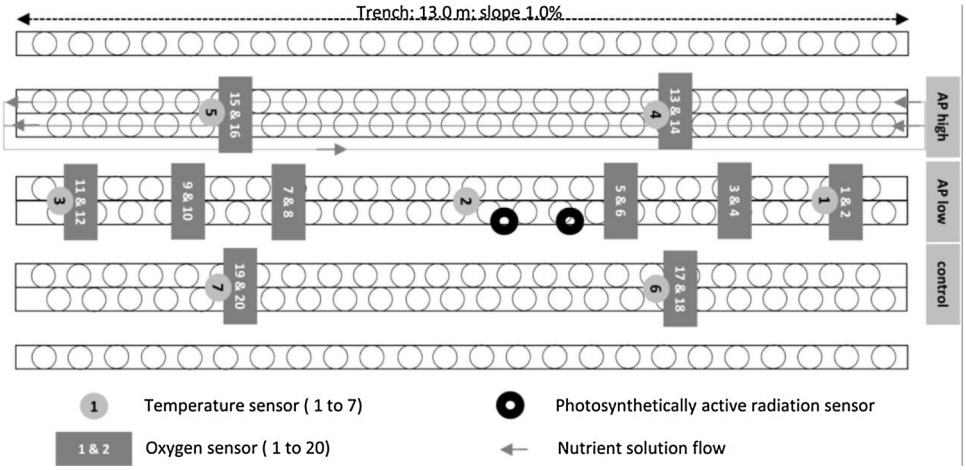

Fig. 2. Ground plan and schematic indications of the control (electrical conductivity (EC) = 1.8 dS m^{-1}) and aquaponics (AP; AP low = EC 1.8 dS m^{-1}; AP high = EC 3.0 dS m^{-1}), as well as the locations of the temperature, oxygen, and photosynthetically active radiation (PAR) sensors.

190R Quantum; LI-COR, USA) were installed in the middle of the greenhouse (Fig. 2). The sensors were installed just above the canopy of the tomato plants, and adjusted in height with the growing crop. The measurements occurred every 15 min and were saved automatically in a data base. For calculation the mean values of both sensors at each time point were used.

2.3. Oxygen concentration/consumption measurements in the cultivation trenches

2.3.1. Oxygen measurement in the cultivation trenches

To investigate the oxygen concentration in the nutrient solution passing the root zone of the tomato plants, a total number of 20 optical oxygen sensors were placed below the continuous flowing nutrient solution surface within the cultivation trenches. The oxygen sensors were installed in February 2015 and kept there during the whole plant production period until end of November. In one of the two trenches per treatment were four (control and AP high) or 12 (AP low) sensors installed (Fig. 2), respectively. In each case two sensors were placed side by side. The distance between the sensor groups in the control and AP high treatments was 6 m. The respective first two sensors (13&14 and 17&18) were installed 3.5 m behind the inflow point of the nutrient solution. In AP low the first two sensors (1&2) were installed 0.5 behind the inflow. The other sensors followed in a distance of 2 m, 4 m, 8 m, 10 m and 12 m from the first sensor.

For oxygen measurement plastic optical fibres were used as described by Holtman et al. (2009a). The fibres contained an oxygen sensitive fluorescent dye (Tris-Ru^{2+} 4,7 biphenyl 1,10 phenantroline) embedded in a polymer coating at the tip (Ast and Draaijer, 2014). All fibres were connected to a measuring device. Via blue light-emitting diodes (LED) blue light pulses with wavelength between 450 nm and 475 nm were sent through the plastic fibres. The life times of the emitted fluorescence light pulses from the dye, which increases with decreasing oxygen concentration, were detected by the measuring device. After digitizing, a processor calculated the oxygen concentration from the fluorescence life times and subsequently into percentage of saturated oxygen concentration (maximum 21%), based on calibrated relationships between oxygen and the fluorescence life time for each fibre. As the sensitivity of the oxygen sensors is slightly different for the different fibres a calibration procedure was applied to each fibre in which the oxygen concentration in air and in a 0% oxygen environment was measured for each fibre.

The oxygen concentrations in percentage in the nutrient solution were successively measured about every 15 min during day and night. Because not only the oxygen concentration itself, but also the fluorescence life time behaviour of the oxygen sensitive dye is affected by the temperature, a temperature correction was implemented for the dye. For this, additional seven temperature sensors were installed in the root zone to measure the temperature of the nutrient solution. Two sensors were used for the control and AP high and three for the trench were plants grew under AP low conditions. Except for one sensor in AP low trench (sensor 2, Fig. 2), all temperature sensors were placed near the oxygen sensors. For correction, the slope and intercept of the correction curve was calculated. Due to its linearity, the actual oxygen concentrations ($O_{2,a}$) were calculated as in the following Eq. (1). As such, $O_{2,m}$ means the measured oxygen concentration.

$$O_{2,a}\ [\%] = slope * O_{2,m}\ [\%] + intercept \quad (1)$$

For representation in the present study, the actual oxygen concentrations ($O_{2,a}$) in % were converted into µmol L^{-1}. The conversion was performed in two steps. At first % was converted to mg L^{-1} (Eq. (2)). At this point, simultaneous a temperature correction occurred. In this case, $O_{2,sat,t}$ is the maximal oxygen concentration in aqueous solution at given temperature and $O_{2,amb}$ is the air oxygen concentration (21%). Using the molar mass of oxygen, the mg L^{-1} was recalculated into the µmol L^{-1} expression.

$$O_{2,a}\ [mg\ L^{-1}] = \frac{O_{2,a}\ [\%] * O_{2,sat,t}\ [mg\ L^{-1}]}{O_{2,amb}\ [\%]} \quad (2)$$

The data were displayed as average values of all corresponding oxygen sensors for each treatment. The chosen line diagrams illustrate the oxygen concentration in the course of the day at three different measuring periods. As such, the 1st measuring period was from 29.04.2015 until 05.05.2015, the 2nd period was from 31.05.2015 until 07.06.2015, and the 3rd period was from 11.06.2015 until 15.06.2015. Additionally, the temperature measured in the nutrient solution and the theoretical maximal oxygen concentration at a given temperature in pure water, were plotted.

2.3.2. Oxygen consumption in the cultivation trenches

To calculate the oxygen consumption ($O_{2,cons}$) in µmol L^{-1} h^{-1} the difference between the oxygen concentration (µmol L^{-1}) in the influx ($O_{2,i}$) and efflux ($O_{2,e}$) solution was multiplied by a factor which is the flow rate (Q) of 69 L h^{-1}, and divided by the volume (V; 64 L) of the nutrient solution in the trenches (see Eq. (3)). The time shift of around four minutes the nutrient solution needed to flow from the inlet sensor to the outlet sensor was not considered because the concentration was measured only every 15 min.

$$O_{2,cons}\ [\mu mol\ L^{-1}\ h^{-1}] = \frac{(O_{2,i} - O_{2,e}\ (\infty))[\mu mol\ L^{-1}] * Q\ [L\ h^{-1}]}{V\ [L]} \quad (3)$$

The data were displayed as average values in total (day plus night) as well as for day and night separately. The data were averaged for two measuring periods (marked as period A and B to keep it apart from the periods 1–3 used for oxygen measurement as described in 2.3.1). The period A was 01.05.2015 until 03.05.2015 and the period B was 05.06.2015 until 09.06.2015. Day and night were defined as time between sunrise and sunset for daytime and between sunset and sunrise for night time. For the calculation, the mean oxygen concentrations of the sensors 17&18 ($O_{2,i}$) and 19&20 ($O_{2,e}$) for control, sensors 1&2/3&4/5&6 ($O_{2,i}$) and 7&8/9&10/11&12 ($O_{2,e}$) for AP low, as well as 13&14 ($O_{2,i}$) and 15&16 ($O_{2,e}$) for AP high were used.

2.4. Oxygen consumption of the different nutrient solutions and fish (waste) water

2.4.1. Collection of samples and labelling

In a follow up experiment, the oxygen consumption of the nutrient solutions itself (without plants) was investigated (also referred to as jar experiment). The samples of the nutrient solutions were taken at two different points of the recirculating NFT system. The samples were taken on the one hand from the inflow of the nutrient solution into the cultivation trenches and on the other hand from the outflow of the trenches. Hereinafter these samples are labelled as “in” and “out” behind the relating treatment label, respectively.

Furthermore, the pure fish waste water used to prepare the respective nutrient solution for AP low and AP high was tested. As such, the samples were taken from the storage tank that was placed in the greenhouse (Fig. 1). Hereinafter these samples are labelled as “fish waste water”.

Additionally, the oxygen concentration in the fish water in the recirculating aquaculture system (RAS) was investigated. These samples were taken directly from the reception tank (between biofilter and fish tanks) of the RAS (Suhl et al., 2016) and are labelled as “RAS water”.

For investigation, 6 samples from each variant were taken (n = 6), and a minimum of four of these were used to calculate mean values.

2.4.2. Investigation of the oxygen consumption of the different nutrient solutions and fish (waste) water

To investigate the oxygen consumption of the different waters (defined in 2.4.1), prepared glass jars with a total volume of 210.92 mL and air tight lids were used. The jars were prepared with a mount to fix

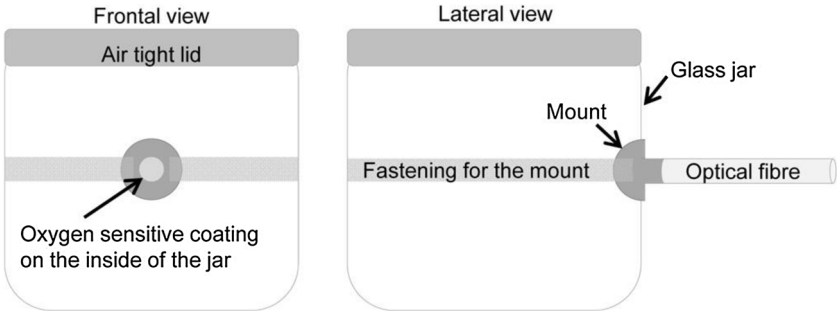

Fig. 3. Schematic overview of the measuring jars used for oxygen consumption measurement.

the plastic optical fibres (Fig. 3). The mounts itself were fixed with simple tape. For the measurement the same fibres and device as described in 2.3.1 were used, but here the oxygen sensitive fluorescent dye coating was not on the tip of the fibre but inside the glass jar at the position of the fibre mount. So, the contact point of the glass and the oxygen sensitive coating herein, was at the tip of the optical fibre outside the jar. This allows the measurement of oxygen concentrations in the airtight closed jar from the outside. For measuring, the glass jars were filled completely with the respective water samples without any air pockets left. Before filling the water into the jars, it was saturated with oxygen by shaking the solution vigorously in a large container. After closure of the jars, the oxygen fibres were fixed tight within the mount to ensure optical contact between the oxygen sensitive coating inside and the fibre outside the jar, and measurements started immediately. The oxygen measuring was performed as described in 2.3.1, but in this case the oxygen concentration was measured every five minutes for each jar. The measuring period per jar was restricted to a maximum of 370 min.

For further calculations, the measured oxygen concentration in percentage was converted to µmol L^{-1} as described in Section 2.3.1. To get information of the oxygen consumption rate ($O_{2,cons}$; µmol L^{-1} h^{-1}), the oxygen concentration in the water samples at the end of the measurement ($O_{2,t370}$) were firstly subtracted from the oxygen concentration at the beginning of the measurement (samples full saturated; ($O_{2,t0}$)). With the knowledge of the measuring time (370 min ≙ 6.22 h), the consumption per hour was calculated as shown in Eq. (4).

$$O_{2,cons}\ [\mu mol\ L^{-1}h^{-1}] = \frac{(O_{2,t0} - O_{2,t370})[\mu mol\ L^{-1}]}{6.22\ [h]} \quad (4)$$

Because of the different course of the decreasing oxygen concentration between the different waters, the oxygen consumption was partly calculated for different measuring periods. For all treatments the oxygen consumption for the whole measuring period (370 min) was calculated. For samples which showed a strong initial decrease, a threshold oxygen concentration was set. Above this threshold concentration of 173 µmol L^{-1} (period 1), the oxygen concentration decreased much faster, as below this concentration. For the samples which reached this threshold concentration, the oxygen consumption was calculated additionally for the time before and after 173 µmol L^{-1} was reached (period 2).

2.5. Statistical analysis

For statistical analysis the statistics software SPSS, package version 19.0 and 22.0, was used. The correlation between the oxygen concentration, the photosynthetic photon flux density (PPFD), and the temperature of the nutrient solution flowing within the cultivation trenches was determined using bivariate correlation. For evaluation, the Pearson correlation coefficients (r) were calculated and tested for significance levels of $p > 0.05$ and $p > 0.01$. The significance levels are characterised by * ($p = 0.05$) and ** ($p = 0.01$).

To analyse significant differences of the oxygen consumption within the cultivation trenches of the different treatments, and between the different nutrient solutions as well as the fish (waste) water, univariate analysis of variance (ANOVA) was used, after normal distribution was confirmed by the Shapiro-Wilk test. The pairwise comparison between the different variants was according to Tukey-HSD (homoscedasticity) or Dunnett-T3 (heteroscedasticity) tests. Not normal distributed data was tested using the Kruskal-Wallis test and pairwise compared using the Dunn-Bonferroni test. The comparison of two samples (oxygen consumption in cultivation trenches during the day and night) was tested using the Mann-Whitney *U* test (normal distribution failed).

Mean values and standard deviation are displayed as numbers in tables and statistical analysis was carried out on a significance level of $p < 0.05$. Significant differences between the treatments are indicated by small or capital letters.

3. Results

3.1. Oxygen concentrations in the cultivation trenches

The oxygen concentrations in the nutrient solutions were measured continuously, and were investigated. Fig. 4a, b and c show in more detail the results for three measuring periods. Generally, for all measuring periods a typical daily fluctuation of the oxygen concentration was observed. While the oxygen concentration decreased during the day, it increased again during night time. In general, throughout the whole measuring period, from end of April until mid of June (Fig. 4a, b, and c), an intensification of the oxygen depletion during daytime was detected. Especially the hot summer season in mid of June (3rd measuring period, 11.06. until 15.06.2015; Fig. 4c) had a strong effect on the oxygen concentration. While in the 1st measuring period (29.04. until 05.05.2015; Fig. 4a) the oxygen concentration during daytime dropped to a minimum of around 150 µmol L^{-1} for all treatments, the oxygen concentration dropped even partly to zero during daytime in the following weeks (3rd measuring period, Fig. 4c). In this context, the correlation analysis showed that the correlation between oxygen concentration and temperature was negative and ranged between -0.607 (1st period) to -0.817 (3rd period) and is shown in Table 1.

However, in the 2nd measuring period it became apparent that the oxygen concentrations under different treatments became more different from each other. In the 2nd measuring period (31.05. until 07.06.2015; Fig. 4b) in both AP treatments a minimum of about 50 µmol L^{-1} (AP high) to 100 µmol L^{-1} (AP low) were detected, while the oxygen concentration in the control declined only to a minimum of 150 µmol L^{-1}. Primarily the AP high treatment showed a strong decreasing oxygen concentration, as it dropped towards 0 µmol L^{-1} during daytime in the 3rd measuring period (11.06. until 15.06.2015). In the same measuring period, the oxygen level in the control and the AP low treatments declined to a minimum of around 148 µmol L^{-1} and 57 µmol L^{-1}, respectively. In the night, the oxygen concentration under all three treatments levelled at around 250 µmol L^{-1} in the first two measuring periods. In the 3rd measuring period the oxygen concertation raised up to a maximum of around 250 µmol L^{-1}, 225 µmol L^{-1} and 200 µmol L^{-1}

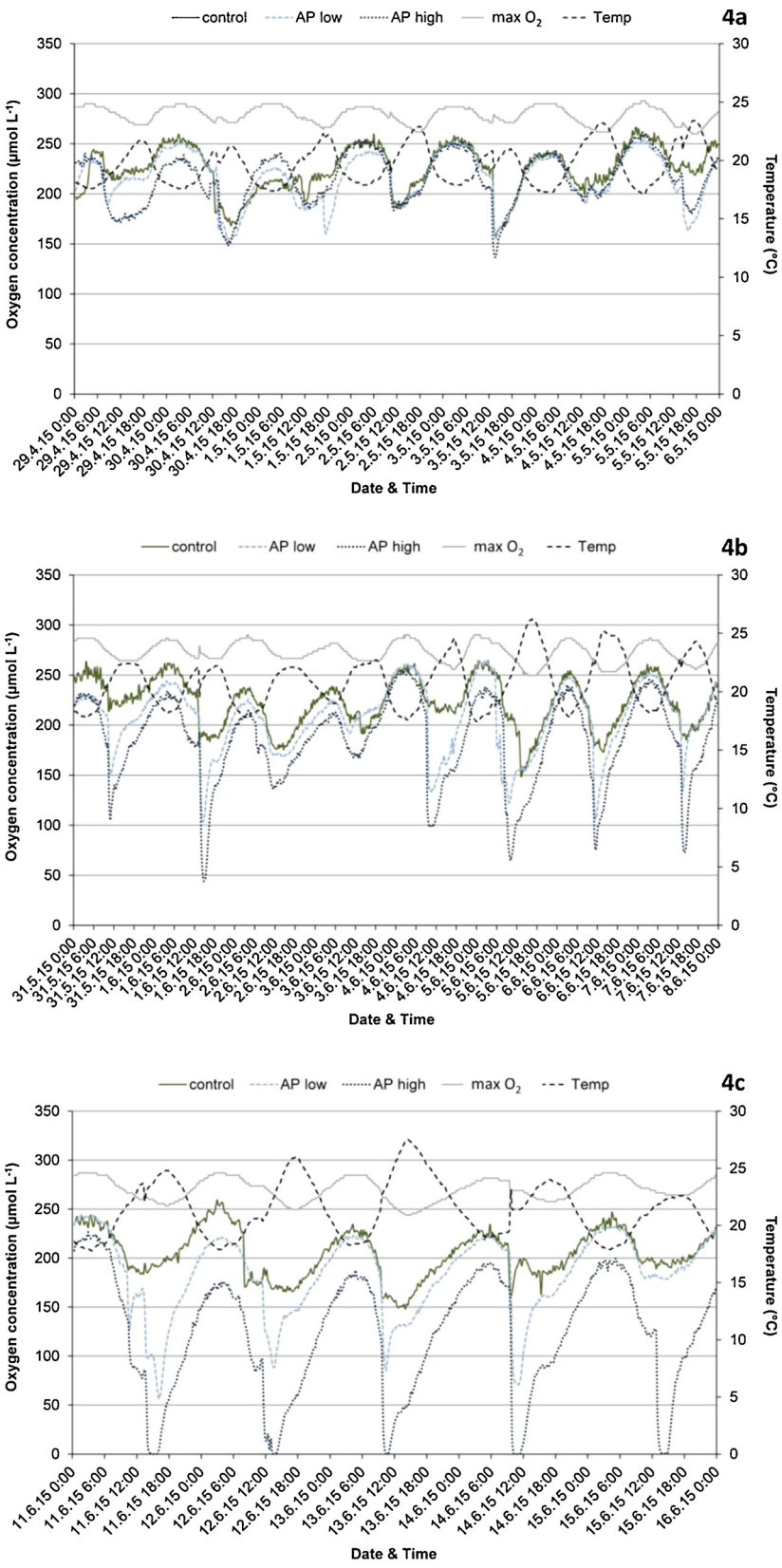

Fig. 4. Mean oxygen concentrations in the nutrient solution for the different treatments: control, prepared with well water (electrical conductivity (EC) 1.8 dS m^{-1}); aquaponics (AP) low (EC 1.8 dS m^{-1}) and AP high (EC 3.0 dS m^{-1}), prepared with fish waste water; and the theoretical maximal oxygen concentration at given temperature in pure water (max O_2). The temperature is the mean value of all sensors, installed in the different treatments. The oxygen concentration was measured every 15 min for three different measuring periods 4a, 4b, and 4c. The sensor measurement locations are marked in Fig. 2. The plotted values are mean values of all sensors per treatment (control and AP high = each with 4 sensor, AP low = 12 sensor).

in the control, AP low, and AP high treatment, respectively. In summary, it was detected that the oxygen concentration in the AP high treatments was generally lower than in both other treatments.

3.2. Correlations between oxygen concentration, photosynthetic photon flux density (PPFD), and temperature

Analysis of the correlation between the oxygen concentration in the nutrient solutions flowing in the cultivation trenches and PPFD showed

Table 1
Pearson correlation coefficient between oxygen (O_2) concentration, photosynthetically active photon flux density (PPFD), and temperature.

Variable	Measuring period			
	1st: 29.04. – 05.05.2015	2nd: 31.05. – 07.06.2015	3rd: 11.6. – 15.06.2015	All periods
Mean temperature (°C)[1]	19.6	20.8	21.4	
Mean O_2 (µmol/L)[1]	232.1	215.4	186.3	
Mean PPFD (µmol m^{-2} s^{-1})	167.3	139.4	181.7	
O_2 * PPFD	−0.568**	−0.648**	−0.689**	−0.557**
O_2 * temperature	−0.607**	−0.784**	−0.817**	−0.773**
PPFD * temperature	0.562**	0.574**	0.576**	0.532**

The values for correlation were mean values of all treatments using all data points collected in the different periods.
[1] The data are mean values for each time point of all three treatments for day and night.
** The correlation is significant with $p < 0.01$.

that there is a negative correlation between both; the higher the radiation the lower the oxygen concentration. The correlation was highly significant ($p < 0.01$) in all considered measuring weeks (Table 1). The coefficient rose from the 1st measuring period ($r = -0.568$) to the 3rd measuring period ($r = -0.689$). A similar pattern was observed for the correlation between the oxygen concentration and temperature of the nutrient solutions. The relationship was also negative ($p < 0.01$) and increased over the measuring periods from End of April ($r = -0.607$; 1st period) until mid of June ($r = -0.817$; 3rd period). It was noticeable that the correlation between oxygen concentration and temperature was higher than between oxygen concentration and PPFD, although PPFD and the temperature were in turn significantly ($p < 0.01$) positively correlated. The positive correlation was very similar ($r = 0.562$ to 0.576) in all measuring periods.

3.3. Oxygen consumption in the cultivation trenches

The oxygen consumption rate in the used nutrient solutions flowing in the cultivation trenches differed significantly between all treatments when 24 h values were considered (24 h; Table 2). When day and night were evaluated separately, the oxygen consumption rate at day and night was equal in control and AP low in measuring period A. The significant highest consumption during period A was found in AP high for all daytimes. In comparison to the control, the consumption was increased by 37.1% (24 h). Latter applied also for period B where the consumption was increased by 88.6% (24 h) in AP high in comparison to the control. Furthermore, in period B all treatments differ significantly in all evaluated times, and the oxygen consumption in the control was significantly lowest. The oxygen consumption in AP low was increased by 17.7% (24 h) compared to control.

The statistical analysis showed furthermore that the oxygen consumption was always significantly higher during the day than during the night (Table 2). The mean consumption during the day was 1.4 (AP high) to 1.7 (AP low) times higher during period A. In period B the differences between day and night increased and were 1.7 (AP high) to 2.8 (control) times higher during the day.

3.4. Oxygen consumption of the nutrient solutions and fish (waste) water

In the experiments in which the decrease of oxygen levels in closed jars (jar experiment) with different solution samples (nutrient solutions, fish waste water, RAS water) were measured, it was observed that the water from the different treatments showed a different course of decreasing oxygen concentration over the evaluated measuring time (Fig. 5). First of all it was noticed that three samples, fish waste water, AP hi-in, and RAS water, showed a course deviating from that of the other samples. The oxygen concentration in the fish waste water dropped clearly the fastest. After a rapid initial reduction of the oxygen concentration in the first 21 min (Table 3), the decrease of the oxygen concentration became smaller. Only in the fish waste water treatment the oxygen concentration dropped to 0 µmol L^{-1} within the measuring period of 370 min. Additionally, the nutrient solution from AP high showed as well a rapid decreasing oxygen concentration after the measurement started. However, the reduction was less strong than in the fish waste water and levelled at around 160 µmol L^{-1} (Fig. 5) after about the first 66 min (Table 3) of fast oxygen reduction. The oxygen concentration in RAS water dropped again less strong and levelled to a minimum of about 190 µmol L^{-1} at the end of the measuring period. All other treatments showed an equal behaviour. The oxygen concentration did not decline very strongly and levelled between 210 µmol $L^{-1}$and 240 µmol L^{-1} at the end of the measuring period.

The consumption rate ranged between 3.8 µmol L^{-1} h^{-1} (control in) and 36.2 µmol L^{-1} h^{-1} (fish waste water) when the total measuring period of 370 min was considered (Table 3). Considering the 370 min, the oxygen consumption in the fish waste water was significantly increased (36.2 µmol L^{-1} h^{-1}) in comparison to all other samples. The consumption was 3.1 times higher than in RAS water. The oxygen concentration of AP high-in and AP high-out differed by 11.8 µmol L^{-1} h^{-1}, and was significantly higher in AP high-in (17.0 µmol L^{-1} h^{-1}). For the other treatments (control and AP low) no difference in the oxygen consumption between the in and out going water in the trenches were detected.

Table 2
Mean oxygen consumption rate in cultivation trenches, operate with nutrient solutions on basis of conventional hydroponics (control) and aquaponics (AP low and AP high) in two different measuring periods.

Measuring period	Measuring time[1]	Oxygen consumption rate (µmol L^{-1} h^{-1})		
		control	AP low	AP high
Period A	24 h	79.8 ± 56.6^{b}	69.6 ± 36.5^{a}	109.4 ± 58.3^{c}
(01.05.-03.05.2015)	Day	91.6 ± 59.6^{aB}	81.9 ± 36.3^{aB}	121.0 ± 55.5^{bB}
	Night	59.5 ± 44.4^{aA}	48.4 ± 25.7^{aA}	89.1 ± 57.6^{bA}
Period B	24 h	58.1 ± 62.2^{a}	68.1 ± 82.8^{b}	109.6 ± 65.7^{c}
(05.06.-09.06.2015)	Day	73.0 ± 60.9^{aB}	79.9 ± 90.9^{aB}	125.5 ± 64.6^{bB}
	Night	26.3 ± 52.4^{aA}	40.1 ± 49.4^{bA}	75.9 ± 54.6^{cA}

The data represents mean oxygen concentrations during a period of three (period A) and five days (period B). Significant differences were analysed by analysis of Variance (ANOVA; normal distribution) and differences were tested using Dunnett – T3 test. Different superscript small letters indicate significant differences ($p < 0.05$) between the treatments within one measuring period. Significant differences between day and night within one treatment and per period were tested using Mann – Whitney *U* test and are indicated by different superscript capital letters. The control and aquaponics (AP) low were prepared with mineral fertilizer up to an electrical conductivity (EC) value of 1.8 dS m^{-1}, and AP high to an EC value of 3.0 dS m^{-1}. The nutrient solution for the control was prepared with well water, and the nutrient solutions for both AP treatments were prepared with fish waste water.
[1]Day = time between sunrise and sunset; night = time between sunset and sunrise; 24 h = mean value day and night.

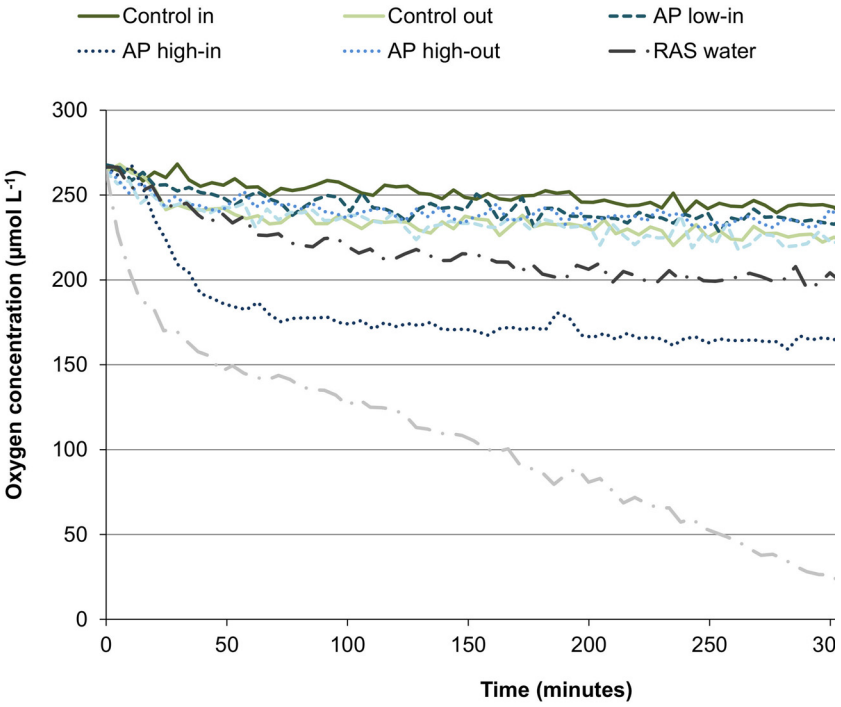

Fig. 5. Oxygen concentrations in the jars filled with different nutrient solutions and fish (waste) water within a measuring period of 370 min. The nutrient solutions for the control were prepared with well water (electrical conductivity (EC) = 1.8 dS m^{-1}) and the aquaponics treatments (AP) were prepared with fish waste water (AP low = EC 1.8 dS m^{-1}; AP high = EC 3.0 dS m^{-1}). "In" and "out" behind the treatments describes the sampling point, described in materials and methods. Lines show average values for at least four jars.

As mentioned above, the nutrient solution prepared with fish waste water and mineral fertilizer for AP high and the pure fish waste water showed a high oxygen consumption rate in the first minutes (Table 3, Fig. 5). The oxygen concentration of the inflow water of AP high decreased below the threshold oxygen concentration of 173 µmol L^{-1} within the first 66.4 min (period 1) and had a significantly higher oxygen consumption rate (83.5 µmol L^{-1} h^{-1}) than the mean value over the whole measuring period (17.0 µmol L^{-1} h^{-1}). After the threshold concentration of 173 µmol L^{-1} (period 1) was reached, the oxygen consumption rate dropped to 3.3 µmol L^{-1} h^{-1} for the rest of the time. The oxygen consumption rate in fish waste water reached 334.5 µmol L^{-1} h^{-1} in the first 21.4 min (period 1) and was also significantly higher when compared to the oxygen consumption rate during the whole measuring period (36.2 µmol L^{-1} h^{-1}) and the consumption rate after it reached the threshold concentration (24.4 µmol L^{-1} h^{-1}; period 2). Only in the latter both treatments (AP high-in and fish waste water) the oxygen consumption dropped below the threshold concentration of 173 µmol L^{-1}during the measuring period.

4. Discussion

As presented in Fig. 4, a continuous daily fluctuation of the oxygen concentration was detected in the cultivation trenches. The decreasing concentration during the day and increasing concentration during the night was found over all measuring periods from end of April until mid of June. However, it was noticeable that the intensity of the fluctuation increased clearly over time (Fig. 4). Especially during the hot summer season in mid of June (Fig. 4c) the oxygen concentration in the trenches dropped clearly over the day. The oxygen concentration in aquatic solutions in general, and in nutrient solutions in particular, is affected by different factors. It is generally known that the amount of soluble oxygen in aquatic solutions depends, among other things (pressure, salinity), on temperature. With increasing temperature the solubility of oxygen decreases (Carpenter, 1966). This might be one factor of the day

Table 3
Oxygen consumption rates of three nutrient solutions and fish (waste) water used to prepare the different aquaponic nutrient solutions, measured in 370 min (total), in period 1 and period 2.

Treatment	Total oxygen consumption rate (µmol L^{-1} h^{-1}) (370 min)	Oxygen consumption rate (µmol L^{-1} h^{-1}) in period 1	Minutes to reach period 2	Oxygen consumption rate (µmol L^{-1} h^{-1}) in period 2
Control in	3.8 ± 1.3$^{a(3)A}$	–		–
AP low-in	5.0 ± 1.7$^{ab(2)A}$	–		–
AP high-in	17.0 ± 1.3$^{d(1)A}$	83.5 ± 10.5$^{(1)B}$	66.4 ± 4.6	3.3 ± 1.6$^{(1)A}$
Control out	4.7 ± 1.5$^{ab(3)A}$	–		–
AP low-out	6.6 ± 0.8$^{b(2)A}$	–		–
AP high-out	5.2 ± 1.7$^{ab(2)A}$	–		–
RAS water	11.5 ± 1.6$^{c(3)A}$	–		–
Fish waste water	36.2 ± 7.3$^{e(3)AB}$	334.5 ± 99.9$^{(3)C}$	21.4 ± 9.1	24.4 ± 5.2$^{(3)A}$

The data represent the oxygen consumption rate during the whole measuring period (total) until the concentration reached the threshold concentration of 173 µmol L^{-1} (period 1), and after the concentration reached this threshold concentration (period 2). The mean values represent the mean of four (1), five (2) or six (3) repetitions ± standard deviation. Oxygen consumption was compared using Dunn-Bonferroni test and significant differences between the total oxygen consumption are indicated by different superscript letters ($p < 0.05$). Significant differences between all values (including until and after threshold concentrations) are indicated by capital letters. "In" and "out" behind the treatments describes the sampling point, described in materials and methods Whereas the nutrient solution for the control was prepared with well water (electrical conductivity (EC) 1.8 dS m^{-1}), the solutions for aquaponics (AP) were prepared with fish waste water (AP low = EC 1.8 dS m^{-1}; AP high = EC 1.8 dS m^{-1}).

specific course and the decreasing oxygen concentration during the day. This was confirmed by the determined correlation between temperature and oxygen concentration (r = -0.607 to -0.817, $p < 0.01$) in the nutrient solutions (Table 1). Such high correlations were also found by Adams (1992) and Gislerød and Adams (1983). The temperature of the nutrient solutions in turn, of course, correlated positively with the radiation (r = 0.562 to 0.576, $p < 0.01$, Table 1). However, the correlation between the oxygen concentration and temperature was higher than between oxygen concentration and radiation. The typical daily course in the present study confirmed the observations by Holtman et al. (2009b). They found also a regular daily pattern with lowest oxygen concentrations during the afternoon when radiation was highest. However, the temperature dependence cannot explain totally the strong decrease of the oxygen concentration in the nutrient solution during the day, especially in AP high. The calculated maximal effect of the temperature on oxygen concentration was 33 µmol L^{-1} (29.04.–05.05.2015), 40 µmol L^{-1} (31.05.–07.06.2015), and 38 µmol L^{-1} (11.06.–15.06.2015). These values were clearly lower than the measured oxygen difference between day and night (Fig. 4). In nutrient solutions some other factors have to be considered. As mentioned in the introduction, the plant itself affects the oxygen concentration due to the oxygen use for root respiration (Chun and Takakura, 1994; Gislerød and Kempton, 1983). For tomatoes, for instance, a root respiration rate of 3.24 µmol O_2 h^{-1} g^{-1} FM to 4.68 µmol O_2 h^{-1} g^{-1} FM was reported by Morard and Silvestre (1996). The root respiration itself is also temperature dependent (Jackson, 1980) and follows a time course with low rates during the night (low root temperature) and higher rates (high root temperature) during the day in consequence of temperature change (Palta and Nobel, 1989). For instance, a positive linear relationship between 9 °C and 20 °C was found for wheat by Morard and Silvestre (1996). In addition, microorganisms living in the root zone consume oxygen (Jackson, 1980; Strayer, 1994) and influence the oxygen concentration within the nutrient solution. Furthermore the growth and metabolisms of microorganisms in turn is temperature dependent and increases with increasing temperatures (Strayer, 1994). Both, the high activity of plants and microorganisms increased the oxygen consumption in the nutrient solution during the day significantly compared to the night (Table 2). The mean oxygen consumption during the day was 1.4 (AP high) to 1.7 (AP low) times higher in period A and 1.7 (AP high) to 2.8 (control) times higher in period B. Besides the higher plant and microorganism activity, the increasing root mass due to plant growth might also intensify oxygen depletion in the nutrient solution during the day and over the whole measuring period from end of April until mid of June (Fig. 4). It was shown that a higher root weight results in an increasing oxygen depletion in nutrient solution (Morard and Silvestre, 1996).

During the measurement of the oxygen concentration in the cultivation trenches it was noticed that the oxygen concentration in the nutrient solutions of the different treatments differed increasingly over time (Fig. 4). While the oxygen concentration was more or less similar in the first measuring period (29.04.–06.05.2015; Fig. 4a), the depletion of the oxygen concentration during the day was stronger in aquaponics than in the control in the following weeks. Especially in AP high a continuous and strong oxygen depletion was measured over time. In the 3rd period (11.06.–15.06.2015, Fig. 4c) the oxygen concentration even dropped to 0 in AP high, while the minimal oxygen concentration in AP low dropped to 57 µmol L^{-1} and in the control only to 148 µmol L^{-1} in the same period. The calculation of the oxygen consumption rate in the cultivation trenches confirmed these measurement results. However, it was detected that the oxygen consumption did not differ between control and AP low in period A (01.05.–03.05.2015), but did differ in period B (05.06.–09.06.2015) (Table 2). It was expected that the differences between AP low and control would have been increased further with passing time. In contrast, the oxygen consumption in AP high was always the significant highest in both periods. The higher oxygen consumption in aquaponics compared to control may be due to a higher microorganism activity and probably to higher amount of (soluble) solids. The decomposition of (soluble) solids consumes oxygen (Masser et al., 1992) and can contribute to oxygen consumption in the aquaponic nutrient solutions.

To investigate the effect of the nutrient solutions itself, without the influence of plants, on the oxygen consumption a further experiment was conducted (jar experiment; see paragraph 2.4). It was found that the oxygen consumption of the nutrient solution mixed with fresh water (control, “in” and “out”) did not differ significantly to AP low-in, AP low-out, and AP high-out (Table 2). In the cultivation trenches the oxygen consumption of control and AP low was also not significant different in period A (day and night). However, in period B the differences were significant for the 24 h period and night, but did not differ during the day. The differences between control and AP low in terms of oxygen consumption within the cultivation trenches (Table 2, period B) could not be explained by the jar experiments (oxygen consumption of nutrient solutions itself). Thus, the differences in oxygen consumption in the trenches between control and AP low were probably not caused by a difference in oxygen consumption of the nutrient solution itself, but more likely by plant related factors (root respiration and/or respiration of microbes attached to the root surface). However, ANOVA revealed a significant effect on the oxygen consumption in AP high-in. However, in general it was interesting that the oxygen depletion in AP low and control was relatively similar, even if AP low was prepared with the same fish waste water as AP high. Therefore, a more similar oxygen consumption, whether in the cultivation trench or in the jars experiment, for both aquaponic treatments were expected. Nevertheless, the significant increased oxygen consumption in AP high-in indicated that the stronger depletion of oxygen, measured in the cultivation trenches (see above) was probably mainly due to a high oxygen consumption of the nutrient solution itself. This in turn could be caused by using fish waste water, what for its part showed the highest oxygen depletion and consumption (Fig. 5, Table 3). However, the latter one would also have increased the oxygen consumption of AP low. Both nutrient solutions, AP low and AP high, differed just in the amount of added fertilizer salt. According to Bloom and Epstein (1984) a moderate increased salt content can increase root respiration, especially in salt sensitive cultivars. As such, the higher salt concentration in AP high might be at least partly responsible for higher oxygen consumption detected in cultivation trenches. For the experiment all samples were saturated at the beginning and the start (saturation) concentration within the samples did not differ (data not shown) even if the salt concentration does have an effect on oxygen solubility (MacArthur, 1916). In addition, it was noticed that only in the AP high nutrient solution, the oxygen consumption dropped significantly by 69.4% from the inflow (17.0 µmol L^{-1} h^{-1}) to the outflow (5.2 µmol L^{-1} h^{-1}). However, in this context it must be considered that only one measuring (point in the cultivation trenches) with two sensors was installed at the inlet and the outlet, respectively, in AP high and control. In AP low, three measuring points with six sensors were installed at the inlet and outlet. The different number of sensors might influence the calculation and results should be interpreted with care. Likely, something changed within the nutrient solution of AP high as it passed the root zone. The reduction of solids by the root mass may play a role, but this would also be the case for affecting the oxygen consumption of AP low-out compared to AP low-in. However, the latter was not determined. Further experiments are necessary to investigate the differences between AP high and AP low.

The differences between RAS water and fish waste water are of further importance. The results showed that something happened to the fish water during its transfer from the RAS to the storage tank. While the oxygen consumption of the RAS water was 11.5 µmol L^{-1} h^{-1} during the measuring period of 370 min, it was 3.1 times higher in the fish waste water. Furthermore, oxygen consumption within the RAS water dropped never below 173 µmol L^{-1}. In contrast, the oxygen concentration in the fish waste water dropped very fast within the first

21.4 min below 173 µmol L^{-1} (consumption rate = 334.5 µmol $L^{-1} h^{-1}$, period 1) and afterwards slower (consumption rate = 24.4 µmol $L^{-1} h^{-1}$, period 2), but as compared to the other samples still fast, to nearly zero. As shown in Fig. 1 and described in materials and methods, the water passed a 3-chamber-pit (3-cp) before it was used to prepare the nutrient solution. As described by Suhl et al. (2018c) it was detected that in the 1st chamber probably denitrification processes occurred due to sludge accumulation and a low oxygen environment. However, a microbiological change may occur in the water as well. It seems reasonable that the number/density of denitrifying bacteria increased in the water passing the 3-cp. Many denitrifying bacteria, e.g. *Pseudomonas* ssp. *and Paracoccus* ssp. which are also present in RAS (Leonard et al., 2000; Sugita et al., 2005), are facultatively anaerobic and can survive and grow also under aerobic conditions in the presence of oxygen (Davies et al., 1989; Patureau et al., 2000). Even if the denitrification is reduced under aerobic conditions, it does not stop totally (Patureau et al., 1996) and depends on growth conditions (Davies et al., 1989). A higher number of bacteria might explain the higher oxygen consumption in the fish waste water, when compared to the RAS water.

Many studies were carried out to investigate the effect of oxygen deficit on plant growth. But well-defined threshold concentrations for oxygen concentrations in nutrient solutions are rare. Schröder and Lieth (2002) recommended in general a level above 60% saturation. Below 60% saturation the growth of barley seedling roots was inhibited (Jackson, 1980). However, Goto et al. (1996) found no negative effect on lettuce growth in hydroponics from a concentration of 2.1 mg L^{-1} (65.6 µmol L^{-1}) and higher (25% of saturation at 24 °C). Jackson (1980) found that the negative effect on leaves occurs at lower concentrations than to roots. While the roots were inhibited below 60% saturation, the leaves were affected only below 10% saturation. According to Gislerød and Kempton (1983) the critical oxygen concentration for cucumber growth is 3 ml L^{-1} (93.8 µmol L^{-1}). Zeroni et al. (1983) stated a critical oxygen value of 50% of oxygen saturation (≙ 125 µmol L^{-1} to 150 µmol L^{-1}) for tomato fruit production, but their recommendations for tomato growth and fruit production is an oxygen concentration of 65% (≙ 162.5 µmol L^{-1} to 193.8 µmol L^{-1}) of oxygen saturation (Zeroni et al., 1983). However, considering of the lower critical oxygen concentration of 4.0 mg L^{-1} (≙ 125 µmol L^{-1}) for tomatoes, the oxygen concentration in the cultivation trenches fell part clearly below the critical concentration in AP high and AP low (2nd and 3rd period; Fig. 4b, and c). Despite the depletion of the oxygen concentration to 0 µmol L^{-1} in AP high during high summer season in the present study (Fig. 4c), the fruit yield and plant growth was not clearly affected (Suhl et al., 2018a). The vegetative growth (number of leaves, total plant length) was similar in all three treatments. The same applies to the generative development (fruit settings, total number of trusses). However, the fruit yield was significantly higher in AP high compared to AP low but not in comparison to the control. The higher yield in AP high was due to a heavier fruit weight (Suhl et al., 2018a). After the strong oxygen depletion detected in the nutrient solution in summer time an air bubble stone was installed in each nutrient solution tank to prevent successfully (data not shown) further strong oxygen depletion during daytime. That the lack of oxygen did not affect the plant growth obviously might be one the one hand due to the short measuring period of absolute lack of oxygen. According to Morard and Silvestre (1996) short and temporary oxygen deficits do not induce irreversible nutritional stress in plants. It was also reported that the ornamental plants *Ficus* and *Chrysamthemum* can probably adapt to constant low oxygen concentrations. Soffer et al. (1991) found that the differences in vegetative growth of both species between low and high oxygen concentrations in the nutrient solution were higher after 47 days than after 88 days. They explained this by presence of an adaptation mechanism. It might be that also the tomato plants in the present study adapt to regularly happening oxygen deficits. On the other hand, in NFT the root mass is usually not submerged completely in the nutrient solution. A part of the roots are above the water surface and can absorb oxygen from ambient air. A further indication that the lack of oxygen in the present study did not affect the plant growth was that the mineral content in the fruit was partly similar (Mg) to the control or even higher (Zn, K) in AP high (Suhl et al., 2018a). It was reported that oxygen depletion results in a decreased nutrient uptake (Morard et al., 2000; Morard and Silvestre, 1996; Stępniewski and Przywara, 1992).

The use of DRAPS is promising for saving water and nutrients but also needs new insights in the crop management requirements in the system. Our results clearly demonstrate that the use of the fish water in tomato cultivation has an impact on the oxygen level in the root zone. Depending on the time of day, as well as the crop developmental status and season the oxygen levels in the cultivation trenches reach very low values when fish waste water was used. These low levels may affect the yield and quality of the crop, as well as make the crop more vulnerable for pathogens (Chérif et al., 1997). In the present study no negative effects on plant growth were detected due to mentioned reasons. Nevertheless, should oxygen depletion occur in NFT, intermitted nutrient solution flow might be an option to guarantee adequate oxygen supply to the roots. Intermitted means an alternation of irrigation and dry period (Economakis, 1993). However, using fish waste water in other hydroponic systems can be problematic. In deep water culture systems, mainly used for leafy vegetable production, the roots are completely submerged in nutrient solution. In these systems the adequate oxygen is in general a challenge and aeration is necessary (Jensen, 1999; Zeroni et al., 1983). In those systems, the use of fish waste water could intensify oxygen depletion. According to the present results it is recommended, especially for aquaponics, to control the oxygen concentration within the hydroponic system to react in a timely manner when oxygen depletion occurs. However, a modified transfer of the fish water directly from the RAS to the storage tank without passing the 3-cp as described by Suhl et al. (2018b), would probably prevent strong oxygen depletion in the nutrient solution prepared with fish waste water. Another possibility to cope with oxygen depletion might be to introduce an UV irradiation device for fish waste water for disinfection to lower drastically the amount if microorganisms.

5. Conclusion

It was demonstrated that fish waste water can have a high oxygen consumption rate which can result in low oxygen concentrations in nutrient solutions in NFT systems. Using fish waste water as in double recirculating aquaponic systems (DRAPS) increased the risk that the oxygen concentration fell to zero during daytime in summer. This is probably due to a higher microorganism activity and a higher content of (soluble) solids within fish waste water as compared to fresh water. However, also the transfer and storage of the fish waste water affects the oxygen consumption of the pure nutrient solution. After transfer and storage the oxygen consumption increased considerably. Additionally, the rate of fertilization of the fish waste water seems to have an effect on the oxygen consumption of the nutrient solution. It seems that a higher EC in the nutrient solution increased the oxygen consumption of the pure nutrient solution. In summary, when fish waste water is used to irrigate hydroponically grown plants a control of the oxygen concentration is highly recommended, especially at high electrical conductivity (≥ 3).

Declarations of interest

None.

Data statement

The data are not summited because the database is very large and complex due to the high measuring interval.

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