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Effects of a special solar collector greenhouse on water balance, fruit quantity and fruit quality of tomatoes

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ABSTRACT

Based on the fact that several regions worldwide and even in Germany are affected by water deficit problems, a new agronomic approach was developed to produce tomatoes (*Solanum lycopersicum* L.) in a sustainable way. The main objective of this study was to investigate the effects of a special solar collector greenhouse consisting of finned tube heat exchangers on the quantity and quality of fruit, water use efficiency and water balance. Changing microclimatic conditions in this system positively affected plant physiological processes, resulting in an increased total yield of up to 31.8% and a decreased total water uptake within the crop of up to 29% when compared with a commercial greenhouse. These conditions led not only to a reduction in the amount of nutrient solution (NS) consisting of valuable fresh water but also to increased water use efficiency (+81%). Furthermore, it was found that the finned tube heat exchangers can be considered as a complex water management system, which can be used to collect high quantities of condensation water. It was calculated that a fresh water supplementation used to mix the NS can be completely omitted when the captured rain and condensation water is reused under the conditions in the solar collector greenhouse. In order to test to what extent the collected condensation water was suitable for irrigation, the effects of condensate-containing NS with a higher Zn concentration (1.74 mg L^{-1}) were examined regarding yield and the ingredients in tomatoes. Compared with an applied NS supplemented with 0.2 mg Zn L^{-1}, condensate-containing NS increased fruit quantity (+39%) and quality, e.g., contents of lycopene (+15%), β-carotene (+13%) and phenolic compounds (+12%). Based on the above-mentioned results, it was concluded that a collector greenhouse can be regarded as a useful tool to increase the yield as well as to reduce amounts of fresh water, and the condensation water can safely be reused in hydroponic systems.

1. Introduction

Nowadays, it is well known that food production in greenhouses is the starting point of a variety of technological innovations designed to reduce phytosanitary problems, to provide the growing population with food and to satisfy the population's health awareness regarding nutritional quality of fruit and vegetables (UNFPA, 2011). However, such developments are accompanied by several disturbing production conditions caused by global development. Not forgetting the high energy consumption in greenhouses and associated high energy costs, water consumption is one of the most cost-intensive resources used in greenhouse production due to the large quantities of water required for irrigation and a worldwide water shortage, especially in arid regions (Hardin et al., 2008; Ozkan et al., 2007; Rout et al., 2008). Based on the lack of freshwater resources in some parts of the world, a large proportion of the world's population (40%) is currently experiencing water stress, which means that appropriate plant production is not viable (Vörösmarty et al., 2000). However, other countries including Germany itself are affected by regional water deficit problems. The Berlin-Brandenburg region, for instance, is characterized by decreasing groundwater and lake levels caused by the long-term effects of soil water removal and general climate warming (Germer et al., 2011). Under such circumstances, and considering that 70% of global water consumption is needed in the agricultural sector for food production alone (Pimentel et al., 2004), responsible water management is absolutely essential. At present, in Israel and Italy, the water use efficiency (WUE) of produced tomatoes under open field conditions amounts to 16 kg m^{-3} and 20 kg m^{-3}, respectively

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(Katerji et al., 2008; Van Kooten et al., 2008). When potted tomato plants were grown in a commercial polyethylene greenhouse in Spain, the WUE could be increased to 25 kg m^{-3} (Reina-Sanchez et al., 2005). Other scientists found that the water use efficiency in greenhouse production is five times higher than in open field production (Stanghellini et al., 2003). Nevertheless, improved WUE in greenhouses might be useful to counteract water deficiency and its effects on fruit and vegetable production.

Several approaches have been undertaken to reduce the water consumption of crops, e.g., external greenhouse mobile shading, genetically modified plants, different salinity levels of the nutrient solution and controlled drip irrigation (Karaba et al., 2007; Lorenzo et al., 2003; Payero et al., 2008; Reina-Sanchez et al., 2005; Zhai et al., 2010). However, the effects of a special solar collector glass greenhouse (collector GH), which was designed for the moderate climatic zone, on WUE, water balance changes and fruit quantity, as well as on the fruit quality of tomatoes are generally unknown compared to those observed in a conventional glass greenhouse (reference GH). In this context, this special solar collector glass greenhouse is defined as a greenhouse facility with an integrated cooling system, which can be used for dehumidification processes and to produce plants with the thermal energy collected with the cooling system inside this greenhouse (Dannehl et al., 2013). The produced energy excess can also be used to cover the basic load for heating in other greenhouses. Compared to a reference GH without a cooling system, the above-mentioned collector GH, consisting of finned tube heat exchangers under the roof, can therefore be considered as transport medium of sensible and latent energy in semi-closed greenhouses but also as a complex water management system. This means that this can be applied as a form of active humidity control, whereby it might be possible to improve the WUE. Most likely, this kind of greenhouse can also be used to collect water for water reclamation when condensation is collected on the cooled finned tubes. Taking all this into consideration, the objective of this study was to increase the WUE of tomatoes and to reduce fresh water consumption for the preparation of the nutrient solution using a collector GH. To demonstrate the possibilities of saving fresh water, the water balance was calculated, including the collected condensation and rain water. In addition to this, the effects of the condensate-containing nutrient solution on fruit yield, macro- and micronutrients, heavy metals, as well as the different quality parameters of tomatoes, such as lycopene, β-carotene, phenols, titratable acids and soluble solids were investigated. These analyses were absolutely necessary to exclude an accumulation of harmful heavy metals or other elements in fruit, which may be transferred from the finned tube heat exchangers into the condensation water, and to estimate if the reuse of the collected condensate can be used for irrigation.

2. Materials and methods

2.1. Experimental set-up

During the annual production in 2011, the experiments involving tomato plants were conducted in two N–S oriented Venlo-type glasshouses at the Humboldt-Universität zu Berlin, in eastern Germany (52°28′2.28″ N, 13°17′57.88″ E). Both greenhouses were constructed with a gross acreage of 307 m^2 and a total height of 6.7 m, where the side walls reached a height of 6 m. The roofs were covered with 4 mm single glass panes and the side walls with double glass panes (4, 8, 4 mm), including an argon gas fill between both glass panes. In addition, a conventional floor level heating system and a thermal energy screen were installed in each greenhouse. The reference GH was operated by a conventional climate control strategy. This means that the floor level heating was set at 17 °C for day and night and the thermal energy screen was closed at a global radiation of less than 3 W m^{-2}. Furthermore, the ventilation in this greenhouse was opened above 24 °C to cool down the greenhouse. In order to control these processes, proportional integral differences were applied. The same control mechanisms were used in the collector GH, whereas new dynamic set-point strategies were applied for cooling, heating, ventilation, and energy screens compared to the reference GH. In this context, the collector GH was additionally equipped with strongly aluminized energy screens in the roof and side wall regions, in order to save energy (Fig. 1). These were also closed at a global radiation of less than 3 W m^{-2}. Furthermore, the collector GH acted as a solar collector, where 16 zinc coated finned tube heat exchangers with a total length of 21.4 m per finned tube were installed under the roof region (Fig. 1). Taking the construction of the finned tubes into consideration, a total cooling surface of 684 m^2 was calculated. Additionally, an electrically operated heat pump was connected to this pipe system in order to maintain a low temperature (7 °C) for the cooling process, where water containing 31% glycol (v/v) was used as a coolant solution. The cooling process in the collector GH was initiated at a temperature of 22 °C followed by the emergency ventilation at 28 °C in order to avoid plant damage. During this process, high amounts of energy were collected by the absorption of sensible heat energy and latent energy caused by the condensation on the finned tube heat exchangers as shown by Dannehl et al. (2013). The generated heat was stored in a rain-water tank (300 m^3) and reused either for direct heating or for indirect heating via the heat pump and integrated heat exchangers (Fig. 1), i.e., using tubular film blowers and a vegetation heating system with a target temperature of 16 °C (day and night), as well as 17 °C (day and night), respectively. This type of energy harvesting is associated, inter alia, with the dehumidification of greenhouses, and was realized by the removal of water vapour by means of condensation on the cooled finned tubes. The resulting excess of condensation water was removed using aluminium-coated gutters, which were fixed below the cooling pipes (Fig. 1). This water was measured automatically with a volumetric dosing system to calculate the water balance, before it was stored in a separate tank in order to reuse it for further experiments. The condensate quantity is expressed as L m^{-2}. If the stored solar energy was not sufficient to heat the collector GH, the identical floor level heating system as used for heating in the reference GH was used with a target temperature of 17 °C (day and night).

The carbon dioxide (CO_2) enrichment was applied in both greenhouses, which was set at a level of 800 ppm for 12 h during daylight hours. However, the CO_2 supply was interrupted in both greenhouses when the ventilation was opened above 10% in relation to the maximum ventilation opening. To obtain the sought levels of CO_2 and heating, as well as to avoid a temperature excess of 28 °C in the collector GH and of 24 °C in the reference GH, all the aforementioned set points for heating, ventilation and CO_2-enrichment were controlled by data obtained from different sensors. In this context, the measurements were forwarded to a central control computer and recorded every 30 s.

2.2. Determination of yield, photosynthesis and transpiration

A net-acreage of 200 m^2 per greenhouse was used to cultivate 800 tomato plants (cv. Pannovy). These were grown on high channels in rock-wool cubes and irrigated via drip irrigation, which was controlled using light summation over the course of the day and by 30% overwatering obtained after each irrigation cycle. During the day, a watering cycle of 150 s was started mainly after 600 W m^{-2} in both greenhouses. When the recirculation of the drain water exceeded 30%, the light summation for controlling the irrigation was adjusted in both greenhouses to achieve the mentioned water overflow.