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Plant factories; crop transpiration and energy balance

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A B S T R A C T

Population growth and rapid urbanisation may result in a shortage of food supplies for cities in the foreseeable future. Research on closed plant production systems, such as plant factories, has attempted to offer perspectives for robust (urban) agricultural systems. Insight into the explicit role of plant processes in the total energy balance of these production systems is required to determine their potential. We describe a crop transpiration model that is able to determine the relation between sensible and latent heat exchange, as well as the corresponding vapour flux for the production of lettuce in closed systems. Subsequently, this model is validated for the effect of photosynthetic photon flux, cultivation area cover and air humidity on lettuce transpiration, using literature research and experiments. Results demonstrate that the transpiration rate was accurately simulated for the aforementioned effects. Thereafter we quantify and discuss the energy productivity of a standardised plant factory and illustrate the importance of transpiration as a design parameter for climatisation. Our model can provide a greater insight into the energetic expenditure and performance of closed systems. Consequently, it can provide a starting point for determining the viability and optimisation of plant factories.

1. Introduction

Expanding cities no longer derive their food supply from their hinterlands, but rely on the global food trade. Given the limited availability of land, water and nutrients, however, the sustainability of these networks is questionable (Newcombe & Nichols, 1979; Rosenzweig & Liverman, 1992; Kennedy et al., 2007; Lambin & Meyfroidt, 2011). Research on urban agriculture, plant factories and vertical farming has attempted to offer new perspectives for robust food production systems for cities. These systems generally focus on the development of local high-density production in closed plant production systems (Seginer & Ioslovich, 1999; Kozai et al., 2006; Kozai, 2013a, 2013b). These systems can also be integrated into (structurally vacant) high-rise buildings for vertical farming.

Agriculture always has relied on sunlight to power photosynthesis. Greenhouse horticulture uses solar energy both for photosynthesis and heating, by creating a (semi-)closed environment. This is one of the reasons for its productivity. Greenhouses create a controlled environment for plant production where excess (solar) energy is discharged by ventilation and deficits can be compensated by heating. As management of microclimate is fundamental to greenhouse agriculture, it relies on a broad body of knowledge, in particular with regard to the related energetic fluxes and requirements.

Commercial vegetable production in closed systems, however, is a relatively new issue. It focuses on the development of new typologies, such as plant factories and vertical farms (Goto, 2012). As a working definition, a vertical farm can be regarded as a multi-storey plant factory. In spite of the possible benefits, an obvious disadvantage of plant factories is the need for artificial lighting for photosynthesis and energy for air conditioning (cooling and vapour removal, both relying on forced air circulation). In particular, the combination of high-density crop production, limited dimensions and lack of natural ventilation is likely to result in a high demand for dehumidification.

The interior climate and the related energetic fluxes of plant factories have to be investigated in order to quantify these additional energy requirements. Closed systems limit the exchange of energy with the exterior climate. As a result, all energy entering the system has to leave the system through forced air circulation and conditioning. As cooling and vapour removal are quite different processes, however, the distribution between sensible and latent heat is a key factor. Therefore, the energy balance must be based on an accurate estimate of the crop transpiration coefficient, i.e. the fraction of the radiation load dissipated by the crop as latent heat.

To this end, it is essential to simulate the energetic behaviour of the crop – how it transpires, reflects light and exchanges heat and radiation. The results of research on the energy profile offer the starting point for

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the discussion on the possible benefits of plant factories compared with traditional greenhouses.

1.1. Objective

The main objective of this study was to explicate the energetic fluxes associated with the production of lettuce in plant factories. In particular, an approach for the estimation of transpiration was formulated and validated in order to illustrate the effect of the crop on the energetic distribution of sensible and latent heat.

1.2. Outline

We propose a model that is able to determine the relation between sensible heat and latent heat exchange and the corresponding vapour flux for the production of lettuce in closed systems. This model is validated by literature research as well as by experiments on the effect of photosynthetic photon flux density, cultivation area cover and vapour concentration deficit on lettuce transpiration. Subsequently the energy productivity of such a plant factory is quantified and discussed.

2. Theoretical background

This section addresses the energy balance and individual energetic fluxes resulting from closed plant production in a building structure. In particular, we specify our adaptation of the Penman-Monteith crop transpiration method, the 'big leaf' model.

2.1. Energy balance

Numerous models exist to analyse the energy balance in various greenhouse typologies, crops and production methods. It is necessary, however, to determine the impact of the plant factory typology on the various energy fluxes and the resulting interior climate. The plant processes play a key role in the total energy balance. In particular the crop transpiration is of paramount importance.

The following literature survey is intended to provide insight into the interdependency of various climatic variables. These data were used to formulate a model calculating the relative share of radiation load that is dissipated as sensible and latent heat.

2.1.1. Standard greenhouse energy balance

Using the greenhouse air as the control volume of interest, the control surface is composed of the glazing, the ground, components within the greenhouse and any open points of entry, including vents and gaps. The transfer of energy across these surfaces involves both sensible and latent heat exchanges (Boulard & Wang, 2000). The energy balance equation for greenhouses is adapted from Sabeh (2007) and is illustrated in Fig. 1 and represented by the following equation:

$$Q_R + Q_F + Q_{Comp} + Q_{Soil} + Q_{Plant} + Q_L + Q_{Vent} + Q_{Heat} = 0 \qquad (1)$$

Q_R represents heat transfer by radiation. Q_F is the heat transfer across the glazing via conduction and convection. Q_{Comp} represents the heat transfer by the various greenhouse components, including structural components and production systems. Q_{Soil} is the heat transfer between the ground and greenhouse air. Q_{Plant} represents the heat transfer by the evapotranspiration of plants, which transfers latent and sensible heat energy to the greenhouse air. Q_L is the latent heat transfer of sensible energy in the air to water in the form of fog droplets. Q_{Vent} represents the heat transfer by natural and mechanical ventilation, which removes energy from the greenhouse via air exchange. Finally, Q_{Heat} is the energy added to the greenhouse using a heating system. This greenhouse energy balance represents a simplified, illustrative model and does not include elements of thermal inertia.

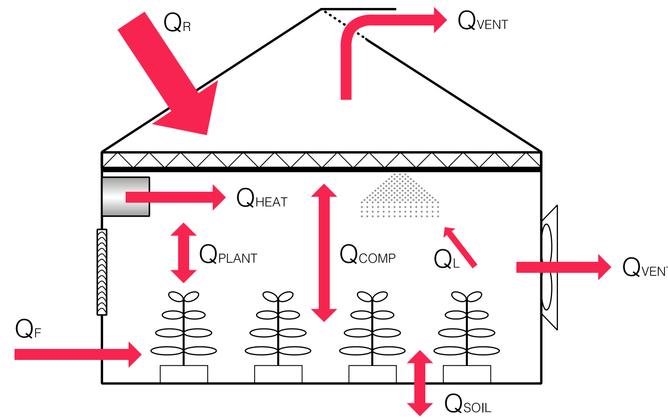

Fig. 1. Green house energy balance.
Adapted from Sabeh (2007).

2.1.2. Plant factory energy balance

The energy balance as stated in Eq. (1) applies to archetypical light-transmitting and naturally ventilated greenhouses, with solar energy as the exclusive source of photosynthetically active radiation (PAR). This equation has to be adapted in order to determine the energy balance for plant factories. The plant factory features a highly insulated construction, which limits thermal exchange with its surroundings. Therefore, the building structure can be considered as adiabatic; Q_{Soil} can also be omitted.

Other differences with the standard greenhouse energy balance include the exclusive use of mechanical air circulation and conditioning for heating and cooling; Q_{Vent} and Q_{Heat} become Q_{HVAC}. The influence of structural elements is integrated with Q_F to become $Q_{Façade}$. Finally, the energetic flux resulting from the inefficiency of production components/systems (e.g. artificial lighting) is redefined as Q_{Equip}. The energy balance for the plant factory is illustrated in Fig.2 and represented by the following equation:

$$Q_R + Q_{Façade} + Q_{Plant} + Q_L + Q_{Equip} + Q_{HVAC} = 0 \qquad (2)$$

The share of Q_R and $Q_{Façade}$ in the total energy balance is likely to be reduced compared to standard greenhouses. This is the result of insulation properties and the relatively small surface area in plant factories, which usually consist of multiple layers. In the case of fully artificial production with an opaque façade the Q_R can be omitted, resulting in the following equation:

$$Q_{Façade} + Q_{Plant} + Q_L + Q_{Equip} + Q_{HVAC} = 0 \qquad (3)$$

Closed production systems allow for a highly steady interior climate. Consequently, the influence of thermal inertia in the energy balance of the facility is very small and is not included in this simplified energy

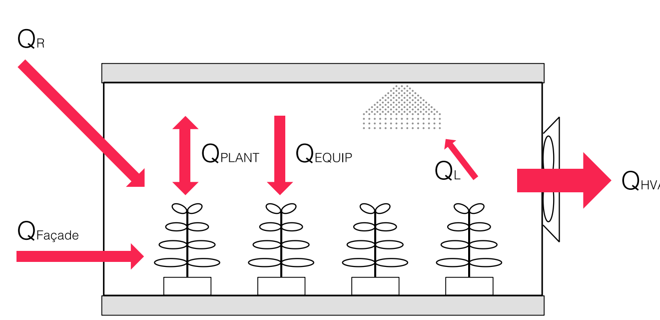

Fig. 2. Plant factory energy balance.