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Research Paper

Development of a grow-cell test facility for research into sustainable controlled-environment agriculture

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ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form
13 June 2016
Accepted 15 July 2016

Keywords:
Agricultural engineering
Sustainable development
Energy efficiency
Automation

The grow-cell belongs to a relatively new category of plant factory in the horticultural industry, for which the motivation is the maximization of production and the minimization of energy consumption. This article takes a systems design approach to identify the engineering requirements of a new grow-cell facility, with the prototype based on a 12 m × 2.4 m × 2.5 m shipping container. Research contributions are made in respect to: (i) the design of a novel conveyor-irrigation system for mechanical movement of plants; (ii) tuning of the artificial light source for plant growth; and (iii) investigations into the environmental conditions inside the grow-cell, including the temperature and humidity. In particular, the conveyor-irrigation and lighting systems are optimised in this article to make the proposed grow-cell more effective and sustainable. With regard to micro-climate, data are collected from a distributed sensor array to provide improved understanding of the heterogeneous conditions arising within the grow-cell, with a view to future optimisation. Preliminary growth trials demonstrate that *Begonia semperflorens* can be harvested to the satisfaction of a commercial grower. In future research, the prototype unit thus developed can be used to investigate production rates, plant quality and whole system operating costs.

1. Introduction

Controlled environment horticulture is a subject nested within the wider agenda of optimising the food system, in order to deal with forthcoming changes in population and climate (Food and Agriculture Organization of the United Nations: FAO (2002, 2015)). Today's established protected crop growth medium is the glasshouse (and related plastic covered systems), globally occupying an estimated 8000 km^2, in which intensive use of pesticides and excess water supply generally takes place (Wainwright, Jordan, & Day, 2014). Hence, there is a considerable effort by stakeholders in the agricultural industry to optimise a range of sub-processes, with the aim to decrease harmful residues and energy inputs.

Such research includes investigations into the physical structure in which plants are grown, and the exploitation of modern technological know-how in order to deploy a higher level of system automation. For instance, significant work has been carried out by the industry to realise what are typically

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http://dx.doi.org/10.1016/j.biosystemseng.2016.07.008

known as plant factories. These are multi-layer growing systems installed in thermally insulated, fixed or mobile buildings, and equipped with artificial light (FreightFarms, 2016; GreenTech, 2016; Hughes, 2015; Kozai, Niu, & Takagaki, 2015; Markham, 2014; Oguntoyinbo, Saka, Unemura, & Hirama, 2015; Ohara, Hirai, Kouno, & Nishiura, 2015; Park & Nakamura, 2015; Payne, 2014; Sugano, 2015). Some immediately perceived benefits are: the flexibility to grow crops at any geographical location, reduced pesticide use and the decrease of food miles, all of which induce savings in terms of transportation costs, greenhouse gas (GHG) emissions and crop nutritional and economic value (Tsitsimpelis & Taylor, 2014). There is also scope for investigation of biological and horticultural issues, for example crop delivery date and flavour, by on-line regulation of the lights and micro-climate.

Plant production by means of artificial climate and artificial or hybrid light dates back to the first quarter of the 20th century. Initially, the primary motivation was to facilitate research into plant responses for different environmental conditions, with illustrative early citations including Harvey (1922), Popp (1926) and Davis and Hoagland (1928). However, thanks to recent technological advances relating to the performance and operating costs of Light-Emitting Diode (LED) lights, it is now possible to realise such facilities for industrial use, with the long term expectation being to outpace the use of greenhouses in terms of production and energy efficiency. A number of systems have been brought into the industrial domain over the past few years, particularly in Japan and the USA (see e.g. FreightFarms, 2016; GreenTech, 2016; Markham, 2014), and interest is expected to further increase as big corporations are investing in the erection of indoor farms (Hughes, 2015; Payne, 2014). Nevertheless, there are numerous on-going research challenges relating to their design and operation. For example, their energy requirements, air movement, dehumidification, internal racking design, different ways to deploy artificial LED lighting, and the monitoring of crop reaction to these.

In principle, a holistic approach to the optimisation of all these will allow for the minimization of total GHG emissions and water consumption, and the concurrent maximization of year round production. Hence, for the research behind the present article, a systems design approach is used to identify the engineering requirements of a new grow-cell facility, with novel contributions made in three interconnected areas. These relate to the systems for mechanical movement and irrigation of the plants, the control of artificial light and an analysis of the environmental conditions inside the grow-cell, including temperature and humidity. The article also provides a selective overview of the literature in these areas, and in this manner aims to provide an introduction to the grow-cell concept and current limitations.

The prototype unit for this research is based on a 12 m × 2.4 m × 2.5 m freight container. As illustrated by Fig. 1, the interior is partitioned into two sections. The first, nearest to the entrance, occupies 2.5 m of the overall length and is used to facilitate control, monitoring equipment and power supply. The main area is further split in half via a motor controlled curtain, with one half presently left empty for access to plants by researchers. The plant growth process takes place in a multi-layer configuration, and light for photosynthesis is provided by LED panels. In the commercial system, the entire container would be given over to plants in order to maximise production. In part for this reason, the growing trays are circulated by means of a novel conveyor system, in which single point irrigation is implemented. The conveyor allows for operator access to the plants and potentially provides for the automatic insertion, inspection and harvest of crops. It also ensures a more equal treatment of plants in terms of environmental variables, and adds to the circulating effect provided by the fans.

One aim of the present research is to optimise the conveyor-irrigation and lighting systems to make the prototype grow-cell more effective and sustainable. With regard to the conveyor, the specific objective is to design a mechanical system with low-power consumption that is adaptable for differently sized grow-cells, and different types of irrigation; and to evaluate the reliability and practical utility of this design in both a laboratory situation and for an illustrative plant growth trial. For the lighting system, the objective is to adapt readily available commercial units so that they are capable of varying the amount of photosynthetic photon flux density (PPFD), and to investigate their spectral characteristics. The subsequent aim is to use these results to optimise the balance between PPFD magnitude and energy consumption in advance of the growth trial.

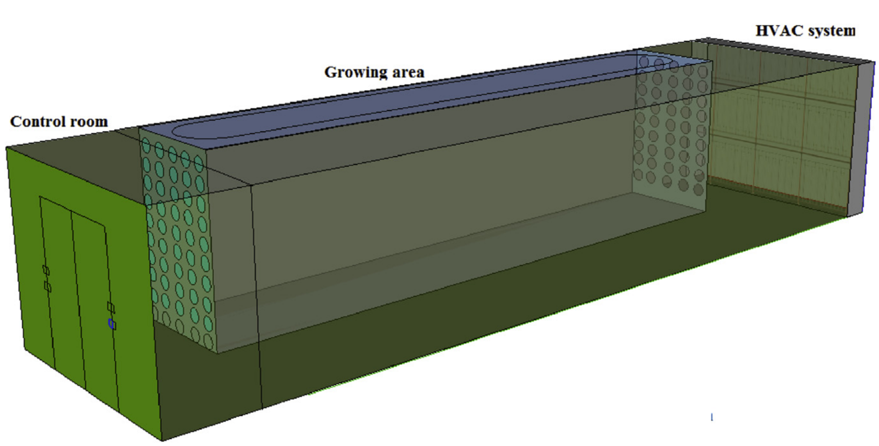

Fig. 1 – Grow-cell prototype drawing showing the basic layout of the modified freight container (12 m × 2.4 m × 2.5 m).