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Research Paper

Field trials of the Natural Ventilation Augmented Cooling (NVAC) greenhouse

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Many greenhouse designs rely solely on natural ventilation, which makes them suitable for use in mild climates or for the production of heat-tolerant crops. The Natural Ventilation Augmented Cooling (NVAC) greenhouse is naturally ventilated and improved by augmenting the thermal buoyancy with a strategically placed misting system. The greenhouse structure comprises tall sidewalls, oversized side vents, a roof vent, and an additional inside roof. The misting system is located above the gutter level of the greenhouse and sprays a mist of water between the top roof and the added inside roof. The added roof guides the cooled air towards the main space of the greenhouse and prevents water droplets from reaching the crop. Testing was performed in Trents, Barbados, where an empty NVAC greenhouse (without plants) provided cooling ranging from 1.3 to 3.6 °C relative to outside temperatures, while increasing relative humidity by 5.7–17.7%. This is in contrast to inside temperatures being warmer than outside temperatures in most natural ventilation greenhouses. The NVAC greenhouse is an affordable design, using far less electricity than a pad and fan system in a comparably sized greenhouse. The NVAC misting system can be used intermittently or continuously to reduce greenhouse temperatures year-round or to extend growing seasons. Site-specific conditions such as natural variations in weather must be considered as they play a role in the performance of the NVAC greenhouse. Accordingly, an automation system can help improve usage.

1. Introduction

Although many active greenhouse cooling and ventilation methods exist, natural ventilation is still widespread in commercial greenhouse operations worldwide (Lee et al., 2003; Perez Parra, Baeza, Montero, & Bailey, 2004). Moreover, many existing greenhouses operating in warmer climates lack proper adaptation to their respective environments; their design and operating strategies are borrowed from operations located in temperate regions, and usually complete their lifespan prematurely or fail from the start. For example, a 1.8 ha greenhouse complex sits abandoned in Barbados, only a few years after its construction, due to design flaws such as poor material and roof design choice, rapid clogging of the cooling pads and high energy costs for the pad and fan cooling system.

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Nomenclature

PAR	Photosynthetically Active Radiation (μmol m^{-2} s^{-1})
RH_i	Average inside relative humidity (%)
RH_m	Average relative humidity during use of the NVAC misting system (%)
RH_o	Average outside relative humidity (%)
T_i	Average inside temperature (°C)
T_m	Average inside temperature during the use of the NVAC misting system (°C)
T_o	Average outside temperature (°C)

Yields and quality of many common vegetable crops reduce at temperatures above 26 °C, even with specialised cultivars (Heuvelink, 2008; Sato et al., 2006). Natural ventilation alone can be sufficient for a few selected crops, but for those plant species that require air temperatures lower than typical outside temperatures, evaporative cooling is the most common solution in the greenhouse industry (Buffington, Bucklin, Henley, & McConnell, 2013; Jensen, 2001). In fact, in arid and semi-arid areas, evaporative cooling is a pre-requisite for extending the growing season (Montero, 2006). Evaporative cooling solutions are useful in most warm climates and a review of existing methods and many other cooling measures is presented by Sethi and Sharma (2007) and McCartney and Lefsrud (2018a), 2018b.

Generally, pad and fan cooling is an effective method of lowering the air temperature of the greenhouse by 4–6 °C if used alone, and 4–12 °C if used with shading (Jain & Tiwari, 2002; Kittas, Bartzanas, & Jaffrin, 2003; Sethi & Sharma, 2007). The main disadvantage of pad and fan systems is the creation of large temperature gradients (up to 8 °C) inside the greenhouse (Kittas et al., 2003), the high energy cost of running the fan and pump systems, and the high water use of the systems (Al-Ismaili & Jayasuriya, 2016). Arbel, Yekutieli, and Barak (1999) showed that the cooling performance of a fog system varied from 8.5 to 12.0 °C, and that the corresponding increase in relative humidity varied from 35 to 68%. However, the efficiency of fog systems is often limited by insufficient natural air convection, in the absence of wind, and by the risk of wetting the plants when water droplet evaporation is not complete (Kittas et al., 2003). Moreover, high-pressure fog systems come at high cost relative to natural ventilation alone (Shen & Yu, 2002). Therefore, natural ventilation and shading methods are still used in many regions of the world with warm climates as they are simple and economically viable (Meca et al., 2013; Rault, 1989). For instance, natural ventilation is still the main means of climate control in the greenhouses of the Spanish province of Almería, which cover tens of thousands of hectares (Molina-Aiz, Valera, Peña, Gil & López, 2009). In this region and other locations using this technology, such as regions in Mexico, China, Colombia and Morocco, summer conditions exceed ideal greenhouse temperatures (Guichard, Bertin, Leonardi, & Gary, 2001; Molina-Aiz et al., 2009), and therefore cooling is often desired to extend the growing season (Kittas et al., 2003; Luo et al., 2005). Similarly, greenhouse production facilities in Australia are located in regions which include temperate, subtropical and tropical climate zones with outside temperatures reaching over 35 °C, putting many crops at risk (Connellan, 2001).

There is a resurgence in protected agriculture in tropical areas such as the Caribbean (DeGannes et al., 2014; Lawrence, Simpson, & Piggott, 2014), and Southeast Asia (Kamaruddin, Bailey, & Montero, 2001). These areas have a growing greenhouse industry. Although relative humidity can be very high in tropical climates, some tropical regions with drier daytime conditions or dry seasons (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006; Kumar, Tiwari, & Jha, 2009; von Zabeltitz, 2011), such as Barbados, can benefit from new evaporative cooling strategies, provided they are financially accessible. The West Indies report an increasing number of protected agriculture structures. Jamaica, St-Lucia and Dominica each report over 200 individual protected structures, but less than 40% of them are in operation due to design flaws making the inside conditions too warm (DeGannes et al., 2014). The inaccessibility to technology, rising cost of energy and the unreliability of power grids results in forced ventilation having limited feasibility for most tropical nations (Buffington et al., 2013; Sachs, 2001). Therefore, both pad and fan systems and fog cooling systems are not used, even if the climatic conditions permit their use.

Considerable research has been devoted to improvements in naturally ventilated greenhouses, however, in most cases, the results are informative but not always applicable (Bakker, Bot, Challa, & Van de Braak, 1995; Mutwiwa, von Elsner, Tantau & Max, 2008). Many authors have discussed solar refrigeration systems of which there are several types (Grossman, 2002). The seawater greenhouse (Davies & Paton, 2005) successfully uses seawater for cooling, instead of freshwater, in a greenhouse providing both cooling and desalination. Cooling by over 10 °C was possible in the hot and arid climates in which the design was intended for. Some systems combine desiccation with evaporative cooling. For example, Jain, Dhar, and Kaushik (1994) compared different types of systems that use liquid desiccants and solid desiccants (Jain, Dhar, & Kaushik, 1995), focusing on hot and humid climates. Davies (2005) proposed a desiccation method combined with evaporative cooling to provide up to 15 °C of cooling, but the concept still presented several practical challenges. Although innovative, these systems, including the seawater greenhouse, remain energy intensive.

Another innovative solution, the Watergy greenhouse, is a concept developed by Buchholz, Buchholz, Jochum, Zaragoza and Pérez-Parra (2006). It is a closed greenhouse with a passive cooling and dehumidification strategy allowing for a reduction of water consumption by 75% and continuous plant production even during hot summer conditions in Southern Spain. During the daytime, hot air rises from the vegetation area through the roof area into the tower (Buchholz, Jochum, & Zaragoza, 2005). The greenhouse temperature during daytime ranged from 20 to 35 °C. To increase the energy and water content of the rising air, it is further humidified in the roof area by sprinklers on an inner roof. This design relies on a tall water tower, water condensation, heat exchange and energy storage.

Hemming, Waaijenberg, Campen, and Bot (2004) worked on a greenhouse design for the tropical lowlands of Indonesia.