NUTRIENT DELIVERY SYSTEMS FOR CROP PRODUCTION IN THE CONTROLLED ENVIRONMENT

Gene A. Giacomelli
Agriculture and Biosystems Engineering Department
Controlled Environment Agriculture Center
University of Arizona
Tucson, Arizona, USA

Keywords: greenhouse, nutrient delivery, controlled environment, aeroponics, irrigation, tomato

Abstract

The foundation of all plant production systems is the effective, efficient and dependable means of nutrient delivery to the plant. The nutrient delivery system directly influences the physical components and the plant culture tasks of the plant management technique within the controlled environment agriculture system. The nutrient delivery system can be described in terms of its mechanism for water delivery to the plant. Examples of an aeroponic root growth system, and a traditional tomato production system, within the controlled environment facilities at the University of Arizona, Controlled Environment Agriculture Center are provided.

1. Introduction

The greenhouse controlled environment offers many opportunities for the design and operation of the crop production system. Greenhouse designs may support a variety of crop production systems, from traditional floral and vegetable crops within the soil-like root zone substrates, to soilless water-based hydroponic systems, to aeroponic systems without any soil or water root zone substrates. The specific design will depend on the crop and its production practices.

The foundation of all plant production systems is the effective, efficient and dependable means of nutrient delivery to the plant. There are controllable processes that must be considered to obtain successful production. These include the control of nutrient water (i.e. the supply side), and the control of the environment (i.e. the demand side). The flow of water from a clean source, can be controlled to the root zone of the plant, through modulation of the nutrient delivery system. Water enters the plant through the roots, flows within the vascular systems, and evaporates from the leaves into the controlled environment of the greenhouse. The control of the environment of the plant affects the bio-physical plant processes, including the water transport. Therefore controlling the environment can influence the demand for water by the plant.

The rate of plant water movement through the transpiration process can be modulated by the watering frequency and duration, the electro-conductivity of the nutrient solution, and the subsequent plant system osmotic potential, as well as, by the microclimate surrounding the...
plant. The goal is to avoid rate-limiting situations, and to prevent short-term stress conditions. Since the energy for the water flow is proportional to the solar radiation, then it is logical that watering frequency and availability be related to daily solar radiation conditions. In addition the age, size, stage of development, and morphology of the plant directly influences the plant water demands. Thus control systems have already been developed which monitor solar radiation at the plant canopy and provide climate conditions and irrigation in proportion.

All greenhouse controlled environment plant production systems (CEPPS) must include the nutrient delivery system (NDS), and the plant culture management technique (PMT), that are integrated and enclosed within a controlled environment agriculture system (CEA).

This paper will discuss the parameters of the NDS, as influenced by the PMT, operating within controlled environment plant production systems. The NDS will be described in terms of its mechanism for plant water delivery. An aeroponic root growth system and a traditional tomato production system within the controlled environment facilities at the University of Arizona, Controlled Environment Agriculture Center will be described.

2. Fundamentals of Controlled Environment Plant Production Systems (CEPPS)

The fundamental component systems of CEPPS include the nutrient delivery system (NDS), the plant culture management technique (PMT), and the controlled environment (CEA).

2.1 Nutrient Delivery Systems (NDS)

The nutrient delivery system (NDS) consists of those hardware components that transport nutrient solution, which includes water and soluble fertilizer, from a central location to each individual plant. The central location may consist of a large storage tank filled with nutrient solution which is pre-mixed, pH balanced, and proportioned with salts. An alternative to the pre-mix nutrient solution storage tank is the on-demand proportioning system that mixes the required amount of nutrient solution from concentrated stock solutions for each watering event. No large storage tanks are required, only smaller stock tanks.

The prepared nutrient solution is pumped to the production area, and is distributed uniformly and directly to each individual plant. For example, distribution may be with micro-irrigation drip emitters, or it may be more broadly distributed to the crop that is grouped into rows or troughs, or alternatively distributed in larger zones, for example on benches, or an entire greenhouse bay, by means of an ebb and flood floor. Some means for control of the nutrient distribution pump is required. Irrigation frequency and duration may be based on fixed time intervals determined from past grower experiences, or be more specific to plant demands, and be based proportionally to measured canopy solar radiation. Examples may include systems of drip irrigated rockwool culture for tomatoes or other large plants, or aeroponic culture of small plants whereby the suspended plant root zone is irrigated with a nutrient spray.

2.2 Plant Culture Technique (PCT)
The plant culture technique includes the procedures that are completed by the grower of the plants in order to produce a healthy crop and final product of desired quality. These procedures or culture tasks are crop specific, and vary with the age of the crop. However, the tasks are directly related to the type of NDS. For example, access by labor to the crop will be affected differently by the procedure of growing on raised benches, such as the aeroponic system, or within troughs on the floor, such as with the rockwool culture of tomatoes.

In general, the tasks necessary for the growth of the plant are specific to the ‘product’ desired from the plant. For example, the product may be vegetative (leaf, stem, or root) or reproductive (flower, fruit, tuber). The interrelationship among the labor to complete the culture tasks, the plant growth habit and the NDS, combine to determine the production program and specific labor tasks that must be completed by the grower. Once known, then mechanization or automation alternatives can be evaluated for the production system in order to improve the labor efficiency or reduce the amount of manual labor required for the crop.

2.3 Controlled Environment (CEA)

The controlled environment includes the greenhouse, or other structure such as a closed growth room, and its environmental monitoring and control systems that are implemented to obtain the desired climate in order to produce a quality crop within a predictable time schedule. The controlled environment must be constructed to be compatible with the needs of the NDS and the PCT. The best environmental control systems are not only effective in providing the desired plant environment, but they are designed and constructed to be unobtrusive within the greenhouse system. They should be physically located so as not to interfere with the plant growth, for example, by shading the crop, or by requiring excessive greenhouse space thereby reducing production per unit area. They should be able to anticipate or measure outside climate changes, diurnal cycles, and sky conditions, and then be capable of automatically adjusting the environmental parameters appropriately for the plants. Ultimately they should be able to directly monitor the plant processes and modulate the environment to maximize crop yields and greenhouse production.

3.0 Controlled Environment Agriculture Center (CEAC)

3.1 Greenhouse Structures and Environmental Control

The CEAC greenhouses are located at the Campus Agricultural Center of the University of Arizona. They serve as teaching, research, and demonstration facilities. One greenhouse includes a hydroponic crop production system that is currently used for tomato, cucumber and sweet pepper production. It serves as the educational, “hands-on”, laboratory for students interested in the study of controlled environment plant production systems. The 484 m² structure includes heating, ventilation, cooling, and fertigation systems, as well as, a microprocessor controller that automatically monitors and maintains the proper environmental conditions. Dr. Merle Jensen and Dr. Pat Rorabaugh were instrumental in the
initial development, implementation, and operation of the greenhouse system for the 2000-2001 academic year and production season.

The metal frame structure consists of two, gutter-connected 7.3 m wide by 33 m long bays. The roof consists of a ‘saw-tooth’ design developed by the Hired Hand Co. for improved natural ventilation and cooling. The glazing consists of rigid, single layer corrugated polycarbonate sheets. The greenhouse superstructure not only provides an enclosed protected area of controlled environmental for the greenhouse crops, but also supports the weight of the tomato, cucumber and pepper crops.

The heating system consists of two, natural gas fired air heaters with electric motor driven fans to distribute the warm air throughout the greenhouse. These are supplemented by four, 75 watt HAF (horizontal air flow fans) located within each bay of the greenhouse, which help to distribute the warm air uniformly within the greenhouse, and maintain air movement among the plants. The HAF are operated at all times that fan ventilation is not occurring.

Ventilation and cooling is achieved by natural convection through vertically oriented roll-up roof vents that are located 4.3 m above the floor, and that extend continuously 33 m, the length of each bay. This is the primary method of cooling during the more temperate season from November through February. Fan ventilation and evaporative cooling are utilized during the remainder of the year. The wet pad is located on the north wall and the exhaust fans are located on the south wall. Outside air is cooled and humidified as it enters the greenhouse through the 15 cm wide cellulose pad which is 1.8 m high and spans 14.6 m, the width of the greenhouse. The cooled air from the pad travels the length of the greenhouse, and then it is exhausted by the fans. The pad and fan system is extremely effective in the Arizona desert climate because of the typically large wet bulb depression. Air temperature reductions of 17°C across the evaporative pads are common.

Atmospheric carbon dioxide is enriched to 500-600 ppm to increase plant growth during day light periods, when there is no ventilation in progress.

A climate control system produced by Q-Com, Inc. provides for monitoring and automated management of air temperature, humidity, and carbon dioxide, as well as solar radiation. Day and night setpoints and subsequent system operations are controlled to provide 18°C (night) and to a range of from 20°C to 24°C (day), depending on sky conditions being cloudy or clear. These parameters are physically controlled by staging the operations of the gas-fired air heaters to raise the internal air temperature, or a combination of the roof ventilation system, the four exhaust fans, and the evaporative cooling pads, to reduce the internal air temperature. The 30% shade screen is used to reduce the internal solar radiation, as well as, reduce the nighttime energy losses during the cold season. The screen is located overhead directly under the slanted roof and is deployed horizontally.

3.2 High Wire Tomato Production System on Rockwool

3.2.1 Nutrient Delivery System for Tomato Production

The nutrient delivery system (NDS) is a drip irrigation system which provides nutrient water directly to the root zone of the plants allowing for efficient application and control.
Pressure compensating plastic emitters (1.9 liters hr\(^{-1}\)) provide an equal amount of water to each plant. Pressurized tap water with electro-conductivity of less than 0.5, low alkalinity and pH of 8 is blended with concentrated nutrient solutions by nutrient injectors. The prepared solution is delivered to the plants through a network of plastic distribution pipelines and lateral lines to each crop row. Irrigation may occur as many as 69 times per day, and provide approximately 60 ml during a 2 minute duration at each watering. Excess irrigation water is collected from the plant root zone and is stored for other uses.

The nutrients are supplied as soluble salts through the drip irrigation watering system. The nutrients are automatically proportioned, injected and mixed into fresh irrigation water by the fertilizer injectors during each watering event. There are three separate stock solution tanks; A, contains calcium nitrate and chelated iron; B, contains macronutrients and all the other micronutrients; and the acid tank contains nitric acid for maintaining a pH of 5.8 in the nutrient solution. The concentrated nutrient solutions are diluted (1:200) and mixed with the water immediately prior to irrigation. This NDS is an active system that requires electrical power for irrigation delivery. Solenoid (on/off) valves, controlled by an automated timing device controls the frequency, duration and location within the greenhouse of each watering event.

3.2.2 Plant Culture Technique (PCT)

The tomato (cucumber and pepper) plants in the CEAC greenhouse are grown within the high wire, continuous production technique for a period of 11 months. Seedlings are transplanted in August; harvest begins by November; and the crop is terminated in June of the following year. The aerial portion of the plant is supported by plastic string which is secured to the stem by plastic clips which are attached at approximately 40 cm intervals. The string extends from the ground upward through to the growing tip of the plant, and then is attached to an overhead supporting wire by a special hook. The hook has the string wrapped onto itself, and as the plant grows, the string is extended by unwrapping it from the hook. The growing point of the plant is lowered from the support hook, and simultaneously, the hook can be moved along the supporting wire. This allows for lowering and leaning the plant, which is important for maintaining the fruit production area of the plant within easy reach for harvest.

Seeds are geminated in 3 cm rockwool cubes, then transplanted into 8 cm rockwool cubes. Final transplant density (2.5 plants m\(^{-2}\)) occurs at 4 weeks from seeding into the greenhouse on the top of rockwool slabs (dimensions 20 cm by 10 cm by 100 cm). The rockwool slabs are wrapped in white polyethylene film and are placed on an insulation layer of 10 cm polystyrene prior to setting on the greenhouse floor, which had been leveled and covered with a white woven polypropylene plastic film.

The NDS is an open system, without recirculation. From 15 to 35% excess amount of nutrient solution is provided during each watering for leaching of nutrient salts from the root zone. A means to collect and store all the drainage solution for other uses was included. The rockwool slabs provide the aggregate root zone medium which is the buffer storage for the plant nutrient water. This system is most practical for larger crops, with low plant density, and that require a long growing period.
Plant culture tasks include leaf pruning, harvest, and lowering/leaning. Disease and insect control is by integrated pest management practices of biological control and environmental manipulation.

3.3 Aeroponic Production of Root Crops

An aeroponic nutrient delivery system was designed as a prototype commercial production unit for the aeroponic production of medicinal root crops in greenhouses (Giacomelli, 2000). Burdock (*Arctium lappa*) a deep-rooted biennial plant was successfully produced within the system.

The advantages that aeroponic production provided for this crop were: ease of access to the long roots, ability to obtain secondary roots which are typically lost during harvest in soil systems, clean root material that is free of soil-borne organisms, and no concern for introducing an invasive weed such as might occur in outdoor field location. Other benefits related to the aeroponic system within a controlled environment included: potential for a more consistent plant growth and production of secondary metabolites, year-round production, higher plant densities, improved nutrient and water management, potential for mechanical harvesting, and potential of multiple harvests from one crop.

Testing and evaluation is currently in progress. The plants are healthy and growing exceptional well. Horticultural and phytochemical yields will be quantified. Marker compounds have been analyzed for estimation of the quality of the phytochemicals available in the roots.

3.3.1 Nutrient Delivery System for Root Crop

The aeroponic unit consisted of a 3.2 cm diameter PVC plastic pipe, “A” frame construction. Its rectangular base ‘footprint’ dimensions were 2.4 m by 1.7 m and it was 0.6 m high. Two, plant growth frames mounted on the top of the base frame created an A-frame cover that reached 1.5 m at the peak. The plant growth frames were constructed of 3.2 cm diameter PVC plastic pipe and were 1 m wide by 2.4 m long. The entire surface of the A-frame structure was covered with an opaque plastic film sheet to prevent the light into, and water spray out from, the root zone, but allowed easy access for observing and harvesting the plant roots. The bottom of the frame was designed to collect the excess nutrient solution and return it to the nutrient solution storage for reuse.

The nutrient solution distribution system consisted of three rows of 1.3 cm diameter PVC plastic pipes mounted 25 cm above the base of the rectangular frame. The nine nozzles with hollow cone spray pattern were spaced within the bottom of the frame beneath the hanging roots to obtain a uniform distribution of water spray to all plants. The nutrient solution for the system was continuously pumped at a rate of 4.5 L min\(^{-1}\) from a 94 L storage tank located below the aeroponic production frame.

3.3.2 Plant Culture Technique (PCT)
Seedlings were germinated in rockwool cubes and transplanted through the plastic film cover of the plant growth frames (i.e. along both sides of the top of the A-frame) at a density of 11 plants m\(^{-2}\). The aerial portion of the plant remained above the plant growth frames, and the root zone of the plant hung within the space below the surface.

The nutrient solution consisted of a modified one quarter strength Hoagland’s solution. The pH and EC were maintained at 6.5 and 1.0 mS cm\(^{-1}\), respectively. A centrifugal pump, located outside of the nutrient tank, was operated continuously in a 30 s on/120 s off cycle.

4. Concluding Remarks

A protected environment must include a structure with automated monitoring and control systems. All successful controlled environment plant production systems, capable of producing the plant or its desired byproducts will maintain these interrelated system components. Greenhouse plant production systems include the nutrient delivery system, and the plant culture management technique, that are enclosed within a controlled environment. The specific plant culture management procedures are directly related to the capabilities of the grower and influenced by the specific nutrient delivery system used.

However, the purpose of the crop production system may not be for harvest of a traditional crop. Plants are now being grown for alternative uses, such as for their natural biological products and biochemical processes which they may provide, either during production or after harvest. Such processes may include the production of a secondary metabolite for the health or nutriceuticals industry; the hyper-accumulation of compounds from the environment, by phytoremediation practices; or, the reduction of atmospheric carbon dioxide and the replenishment with oxygen within closed, recirculating atmosphere systems. NASA is especially interested in utilizing the plant photosynthetic and respiratory biochemical processes within closed environment life support systems for human space travel.

Innovation in the development of plant production systems allows for unique applications in traditional [earth-based] and non-traditional [extraterrestrial] applications. Fundamental engineering design will be inherent in all successful applications. The understanding of basic biological processes and how they are influenced by their environment is important for success in controlled environment agriculture.

5. Acknowledgement
Support provided by the Controlled Environment Agricultural Center, University of Arizona. University of Arizona, College of Agriculture and Life Sciences, and by an SBIR grant from NIH for Native American Botanics, Inc. Paper # I-125933-02-00. NDSTaiwanPaper2001edited.doc)

6. References
Tsukuba, Ibaraki, Japan. Organized by the National Research Institute of Agricultural Engineering, MAFF Science and Technology Agency, Japan.