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DEVELOPMENT OF A SIPHON SYSTEM WITH POROUS TUBES FOR MAINTAINING A CONSTANT NEGATIVE WATER PRESSURE IN A ROOTING MATRIX

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Tibbts T. W., Cao W. and Frank T. *Development of a siphon system with porous tubes for maintaining a constant negative water pressure in a rooting matrix.* BIOTRONICS **24**, 7–14, 1995. A reliable and effective water and nutrient delivery system with porous tubes has been developed for growing plants at a controllable, constant, negative water pressure. Multiple porous stainless steel tubes were positioned 4 cm apart in a shallow tray (44 cm long, 32 cm wide and 8 cm deep), and then covered with a 4 cm layer of fine medium ($\leq$1 mm in diameter). Nutrient solution was recirculated through the porous tubes under a negative pressure maintained with a siphoning procedure. A range of negative pressures from 0 to 2.0 kPa in the rooting matrix were obtained by changing the length and diameter of inlet and outlet tubing, and/or the heights of inlet solution and outlet tubing end. Multiple growing trays, with similar or different pressures, can be maintained with a single system. The system has shown to be effective for growth of potato plants.

Key words: Controlled environment; microgravity; hydroponics; water stress

INTRODUCTION

Plant growing systems for use in space (microgravity environments) require a unique design to deliver water and nutrients where there is no gravity to avoid excess liquid accumulation around the roots. The systems must be safe and reliable to confine the solution and prevent the release of any free water. A significant amount of effort has been directed toward the development of systems for use in microgravity environments. Several techniques have been proposed to maintain negative pressures, such as the use of acrylic membranes (*6*), hydrophilic microporous ceramic tubes (*1, 2*), stainless steel porous plates (*3*), and stainless steel porous tubes placed in a solid matrix (*4, 5*). Ground experiments have shown that under moderate negative pressures, these growing procedures can effectively produce food with several crop species (*1, 4*).

The systems for microgravity have been developed with active control

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systems that maintain a uniform negative pressure for extended periods of time (*1, 2, 4*). However, these systems will likely be prohibitively expensive for ground based studies that require multiple treatments and replication.

We describe in this report a low cost, negative pressure nutrient delivery system that is reliable and easily managed for ground base research. The described system is a recirculating solution system using porous tubes and a siphoning procedure that can maintain multiple growing trays without additional control apparatus. Individual trays are filled with fine particle medium and can be maintained at similar or different negative pressures. This system provides the opportunity of maintaining a uniform soil water moisture level for plant research that can eliminate the soil moisture variations imposed by most watering procedures and also can effectively avoid the problems of excess soil moisture following water additions. In addition, this systems has application for studying plant response to varied soil moisture stress.

SYSTEM DEVELOPMENT

The complete plant growth system includes growing trays, delivery tubing, supply and return reservoirs, pumps, float, pressure monitoring, and pH control, as illustrated in Figure 1. The key process in the system is the use of a siphon to create a negative pressure inside the porous tubes. To achieve this negative pressure, the solution level in the supply reservoir has to be lower than the porous tubes, but higher than the end of the outlet tubing.

The growing trays were constructed to accommodate the use of sintered stainless steel porous tubes that were 1 cm in outside diameter (0.7 cm ID) and 35 cm long with pores of $\simeq$ 50 micron diameter and air entry value of $\simeq$ 2.0 kPa of water (Astech, Inc, Summit, NJ). Stainless steel tubes with smaller pores that permit development of tensions to 10 kPa are available (Mott Metallurgical, Wheaton, IL). Also ceramic porous tubes and low-priced plastic porous tubes have potential application in this system. The trays were constructed from 0.635 cm thick grey PVC sheet, with an inside dimension of 44 cm length, 32 cm width and 8 cm depth. The trays consisted of two side pieces, two end pieces, and a bottom plate. The sides and ends were 'notched' to allow them to be pressed together and positioned onto the bottom plate. At the outer edge of the bottom plate, small pieces of PVC were glued to keep the sides in place. A liner of black polyethylene sheet was cut to line the bottom and sides of tray. The width of the tray was such that the porous tubes would extend 1.5 cm beyond each side to facilitate their connection to the manifolds. A row of ten holes (4 cm apart) were drilled in the sides centered at 1.5 cm from the bottom for the porous tubes. These holes were 0.2 cm larger than the diameter of the porous tubes. It is noted that the cost of sintered stainless steel tubes is high, yet porous sintered plastic tubes are less costly and can be effectively utilized (Porous Technologies, Fairburn, GA).

Inlet and outlet manifolds were installed around the ends of the porous tubes. The manifolds were cut from 2.54 cm square grey PVC pipe and the

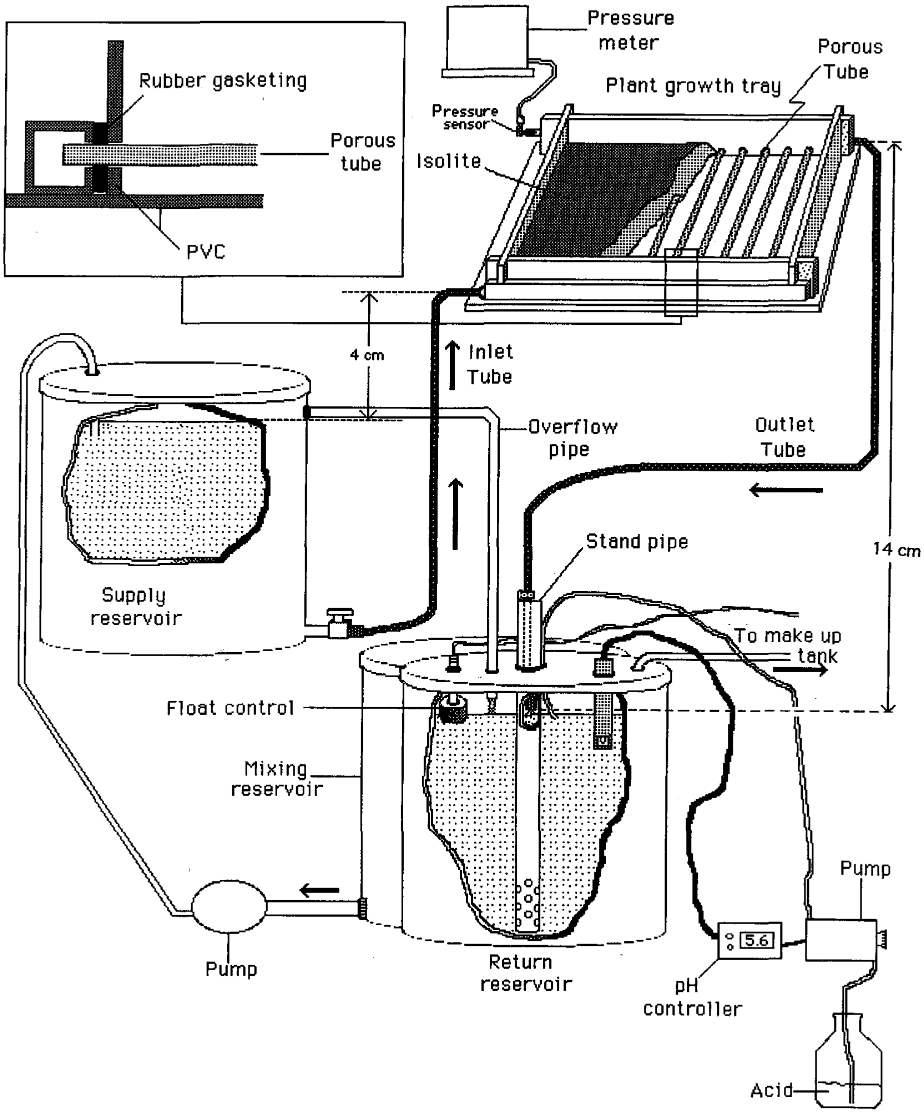

Fig. 1. Schematic diagram of the porous tube system for maintaining constant negative water pressures in a rooting matrix using a siphon procedure.

inside volume was large enough to allow uniform pressure for each of the porous tubes. Holes for the porous tubes were drilled through one side to match the holes in the tray sides. A strip of medium grade nitrile rubber sheet (Buna–N obtained from McMaster–Carr, Chicago, IL), 0.635 × 2.54 cm × 44 cm, was used to seal the porous tubes into the square PVC tube. The rubber sheet was punched with holes slightly smaller than the diameter of the porous tubes and then sealed to the PVC tube using "Plumbers' goop". The tubes were inserted through the holes and extended into the manifold. Ends for the manifolds were cut from 0.635 PVC sheet to a size of 2.54 × 2.54 cm and attached using an epoxy glue. The ends were drilled and threaded for polyethylene fittings that were used for attachment of the inlet and outlet solution tubes and for

Table 1. Tubing requirements to obtain various negative pressures at a flow rate of 150 ml min^{-1}.

Pressure (kPa)	Distance below porous tubes (cm)		Length of tubing (cm)			
			Inlet			Outlet
	Inlet[z]	Outlet[y]	3 mm	6 mm	9 mm	6 mm
0.5	4	14		32	250	250
1.0	4	18		250		250
1.5	4	25	16	250		250
2.0	4	32	32	250		250

[z] Solution level in supply reservoir.

[y] End of outlet tubing.

attachment of a pressure transducer.

Before final tray assembly, all porous tubes were immersed in water for at least 10 hours to fill the capillary pores of the tubes. Then, the porous tubes were inserted into the container sides, and pushed into one manifold until the other ends of the tubes were flush with the opposite side of the tray. The tubes were pulled out of the first manifold while being pushed into the second one, until each tube was centered between the manifolds. This assembly procedure should be undertaken immediately before complete system setup.

Black polyethylene tubing was used for solution flow to and from the trays. Preliminary tests were made to determine the length and diameter for the inlet and outlet tubing. This determination was dictated first by the minimum length of tubing required to extend from the growing trays to the supply and return reservoirs. To obtain the desired pressures and flow rates, the inlet tubing was varied in length and diameter whereas the outlet tubing was fixed at 6 mm inside diameter and 250 cm length (Table 1).

A 200-liter tank was used as a solution makeup tank. The tank outlet was fitted with a solenoid valve and centrifugal pump. The solution from the makeup tank was directed to the nutrient return reservoir (20-liter container) of the system. Nutrient solution from the separate growing trays also returned to this reservoir through the outlet tubes that led into a vertical stand pipe (1.5 cm ID PVC) extending from inside the reservoir. The individual outlet tubing from each tray was fitted with a tubing clamp to maintain the desired outlet tubing position. This clamp, resting on the top of the stand pipe, could be adjusted to provide careful regulation of height of the outlet tubing end. A float and a pH probe were installed in the return reservoir. The float operated the pump from the makeup tank to maintain a constant level of nutrient solution in the return reservoir. From this reservoir, solution entered a second container (mixing reservoir) that was used as a buffer for thorough mixing of fresh and recirculated solution and mixing of acid added for pH control.

The outlet of the mixing reservoir was connected to another centrifugal pump, which pumped liquid to the 20-liter nutrient supply reservoir. This reservoir supplied solution for the growing trays and was fitted with an outlet valve for each tray. The nutrient solution in the supply reservoir was kept at a constant level by pumping in the solution at a rate that exceeded the tray use and having an overflow that led back to the mixing reservoir.

Pressure was measured using Motorola MPX2010D GVS pressure transducers. These transducers were mounted to a short piece of polyvinyl tubing on the end of the supply manifold on each tray. These sensors were connected via a switch to a circuit designed by the Wisconsin Center for Space Automation and Robotics at the University of Wisconsin. The output of this circuit was measured using a digital multi–meter. The sensors were individually calibrated at several pressure levels against a "U–shaped" manometer filled with distilled water. The output for each pressure sensor varied, but all were linear.

Control of pH was accomplished with a digital controlling pH meter and a pH probe placed in the return reservoir. The output of the controller was connected to an electronic control circuit. This circuit included a solid state relay to turn on an "Instrument Mini–pump" (Milton Roy Company, Petersburg, FL) to adjust pH in the return reservoir by adding acid solution at a flow rate of $\simeq$ 40 ml h^{-1}. This electronic circuit also had an adjustable cut–off timer to prevent an excess of acid being added. If the pH adjustment period exceeded a preset duration, the pump would be switched off and require a manual reset.

SYSTEM CALIBRATION

Before system setup, careful measurements and calibrations were undertaken. The porous tubes were first washed with ethanol to remove any oils and residues from manufacturing. For this purpose, the porous tubes were submerged for a few minutes in 95% ethanol bath. After this, the ethanol was removed from the porous tube with a suction pump attached via a liquid trap. Then, the tube was allowed to dry in an oven.

Next, a determination was made of the positive pressure at which air could be forced through the pores after saturating the tubes with water. The tubes were submerged in distilled water and air was carefully removed from inside of the tubes by tipping the tubes while submerged. The tubes were left submerged in water for 24 h to fill the capillary pores with water. At the end of this period, one end of a tube was connected to a regulated compressed air source while the other end was connected to a U–tube manometer. The porous tube, while under water, was slowly pressurized until a stream of air was observed to bubble from the tube. The pressure, as read from the manometer, was considered to be the 'air entry' pressure for the tube. Commonly, the tubes produced bubbles at 2.5 kPa of pressure. Tubes that produced bubbles at less than 2.0 kPa of pressure were discarded.

After installing the tubes and manifolds in the trays, each tray was checked again for possible leakage. With the assembled tray immersed in water, the inlet opening of one manifold was connected to a regulated compressed air source and the other manifold opening plugged. The tray unit was slowly pressurized with compressed air until air began to bubble from the porous tubes. Any leakage of air from connections or fittings was sealed.

Pressure sensors were calibrated using a manometer. The sensor and manometer were connected to a 'tee' shaped fitting and the other branch connected to a water column in an open-ended tube. This water column provided a source of variable negative pressures by changing the height of the water column. Care had to be taken to ensure that there was no liquid in the connecting tubing. The output of the pressure sensor was monitored with a voltmeter. Calibration values for the pressure sensor were obtained for 0.5, 1.0, 1.5, and 2.0 kPa.

After the system was assembled, the desired pressures and flow rates were obtained in the trays by careful regulation of 1) the solution level in the supply reservoir, 2) height of outlet tubing end, 3) height of the growth tray, and 4) length of the inlet tubing. Since a length of *inlet* tubing was selected before system assembly to obtain the approximate desired pressures and flow rates, a readjustment of the inlet tubing length was usually not needed for the fine regulation. It should be noted that the level of solution in the supply reservoir was positioned at a height below the porous tubes but not lower than the negative pressure to be maintained. This vertical distance between the porous tubes and supply reservoir solution, along with the height of outflow tubing end, is critical for regulating the negative pressure and preventing flooding in the event of flow interruption on the outlet side of the tray.

SYSTEM SET-UP

The separate trays were first arranged in an appropriate layout. In our set-up, the growth trays were placed in a circle with the supply and return reservoirs placed in the center. Rigid PVC tubing was utilized for connections between reservoirs. Flexible polyethylene tubing was utilized for inlet and outlts to and from the trays. Each tray was carefully leveled and then all trays were positioned at the same height (±1 mm). After turning the pumps on, each tray was lowered until solution was coming out of the outlet tubing and then the tray raised back to its original position on the platform. A slight suction on the outlet tubing was usually required to start the flow.

After flow was initiated, remaining air in the tubes and manifolds was removed by slightly elevating the outlet side of the tray allowing the air bubbles to flow out of the outlet tubing. This step was repeated 2–3 times over a 2 hour period before measuring pressure and flow rate. If the air bubbling was continuous or found in succeeding days, small air leaks were present and would have to be eliminated. Elimination of all leaks was essential to maintaining constant pressure and flow in each tray.

All reservoirs and fittings were covered with aluminum foil to prevent light penetration and algae growth.

A plant growing medium with particle diameters of 1 mm or less as sand, arcillite (calcined montmorillinitic clay), and isolyte (porus ceramic) was used as a rooting matrix in the trays. A 4–5 cm layer of medium appears to be sufficient to ensure uniform delivery of nutrient solution. The individual trays were covered with an opaque polyethylene plastic sheet, white outer–surface and black inner–surface, to exclude light penetration and minimize medium warming. Openings were made in the plastic sheet for transplanting plants into the medium.

Water pressures and flow rates were carefully adjusted with solution flowing through the porous tubes and after filling the trays with the medium. Fine adjustments of pressure and flow were made so that the variation in pressure and flow among the trays was no more than 5% of desired set points. To minimize the variation in pressure, the height of outlet tubing end for a particular tray was adjusted first. Then if necessary, the height of the tray was raised or lowered a few millimeters to obtain the desired pressure and flow rate. It was necessary to wait at least 30 min after each adjustment before reading pressure and flow rate because the moist media acted as a buffer to pressure changes. During the experiment period, pressures were checked daily and flow rates weekly, and fine adjustments made as needed.

Nutrient solution pH was maintained with a pH controller. The acid solution (H_2SO_4) was started at a concentration of 0.1 M and then incrementally raised to 0.5 M over the experiment period. Both pump speed and acid concentration were adjusted so that the pH in the return reservoir did not fluctuate markedly and consumption of the acid solution was less than 200 ml per day.

In our experiments with potatoes, the established porous tube system has been operated for several months without problems.

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