POTATO GROWTH AND YIELD USING NUTRIENT FILM TECHNIQUE (NFT)

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Abstract

Potato plants, cvs Denali and Norland, were grown in polyvinyl chloride (PVC) trays using a continuous flowing nutrient film technique (NFT) to study tuber yield for NASA's Controlled Ecological Life Support Systems (CELSS) program. Nutrient solution pH was controlled automatically using 0.39M (2.5% (v/v) nitric acid (HNO_3), while water and nutrients were replenished manually each day and twice each week, respectively. Plants were spaced either one or two per tray, allotting 0.2 or 0.4 m^2 per plant. All plants were harvested after 112 days. Denali plants yielded 2850 and 2800 g tuber fresh weight from the one- and two-plant trays, respectively, while Norland plants yielded 1800 and 2400 g tuber fresh weight from the one- and two-plant trays. Many tubers of both cultivars showed injury to the periderm tissue, possibly caused by salt accumulation from the nutrient solution on the surface. Total system water usage throughout the study for all the plants equaled 709 liters (L), or approximately 2 L m^{-2} d^{-1} (7.2 mmol $m^{-2}d^{-1}$). Total system acid usage throughout the study (for nutrient solution pH control) equaled 6.60 L, or 18.4 ml m^{-2} d^{-1} (7.2 mmol $m^{-2}d^{-1}$). The results demonstrate that continuous flowing nutrient film technique can be used for tuber production with acceptable yields for the CELSS program.

Compendio

Se mantuvieron, en bandejas de cloruro de polivinilo (PVC), plantas de papa, cvs Denali y Norland, utilizando una técnica de flujo contínuo de una película (capa muy delgada) de solución nutritiva (NFT), para estudiar el rendimiento en tubérculos, para el programa de Sistemas Controlados de Apoyo a la Vida Ecológica (CELSS) de la NASA (National Aeronautics and Space Administration's). El pH de la solución nutritiva fue controlado automáticamente utilizando ácido nítrico (HNO_3) al 2.5% (v/v), mientras que el agua y nutrientes fueron repuestos manualmente cada día y dos veces por semana, respectivamente.

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Las plantas se espaciaron a razón de una o dos plantas por bandeja, asignando 0.2 a 0.4 m^2/planta. Todas las plantas fueron cosechadas después de 112 días. Las plantas de Denali rindieron 2 850 y 2 800 g en peso fresco de tubérculo en las bandejas con una y dos plantas, respectivamente; las plantas de Norland rindieron 1 800 y 2 400 g en peso fresco de tubérculo en las bandejas con una y dos plantas. Muchos tubérculos de ambos cultivares mostraron daños al tejido del periderma, causados posiblemente por la acumulación de sales de la solución nutritiva sobre la superficie. El total de agua utilizada en el sistema para todas las plantas durante el estudio fue de 709 litros (L), o aproximadamente 2L $m^{-2}d^{-1}$. El total de ácido usado por el sistema a lo largi del estudio (para el control del pH de la solución nutritiva) fue de 6.60L, o 18.4 cm^3 $m^{-2}d^{-1}$. Los resultados demuestran que la técnica de la película nutritiva de flujo contínuo puede ser utilizada para la producción de tubérculos, con rendimientos aceptables para el programa CELSS.

Introduction

As a part of the United States National Aeronautics and Space Administration's (NASA) preparation for long-term space travel, studies have been conducted to examine the use of plants for human life support. The intent would be to use the plants to supply both food and oxygen, while simultaneously removing CO_2 from the atmosphere and minerals (salts) from waste water. In addition, condensate from leaf transpiration could be utilized as a source of potable water for humans or recycled back to the plant nutrient solution. This program has been entitled "CELSS," Controlled Ecological Life Support Systems (MacElroy and Bredt, 1985). To date, a prime focus of the CELSS program has been to study the culture and potential yield of various crops under controlled environment conditions. These studies have involved potato, wheat, soybean, lettuce, and sweet potato (Tibbitts and Alford, 1982). The studies with potato have shown that yields nearly twice that of exceptionally high field yields can be obtained in controlled environments, provided the photosynthetically active radiation, CO_2, temperature, and nutrients are maintained near optimal levels (Wheeler and Tibbitts, 1987; Wheeler and Tibbitts, unpublished).

Because of the substantial payload costs of launching large quantities of mass into orbit, it is likely that plant production systems designed for use in space will use only minimal amounts, or possibly no solid media for plant maintenance, *i.e.*, soilless culture. Likewise, launching large quantities of water will be costly. Nutrient film technique (NFT) provides an approach to plant culture where solid rooting media are eliminated and total water volume can be minimized (Cooper, 1979; Jones, 1983). In most NFT systems, plants are grown in troughs or trays through which a thin film of nutrient solution is continuously circulated to supply water and mineral nutrients to the roots. Little information has been published on potato growth in soilless systems, although recent studies indicate that NFT and aeroponics may have possible commercial applications in the potato industry for certified seed production (Boersig and Wagner, 1988). Previously reported CELSS production data for potato in controlled environments have been gathered from plants grown in containers with solid media, *e.g.*, peat-vermiculite (Wheeler and Tibbitts, 1986, 1987). In addition, these studies have only used the nutrient solution in a single-pass fashion, *i.e.*, the solution was not recirculated. In this report, results are presented from a study in which potatoes were grown to harvest without the use of any solid rooting medium and the nutrient solution was continuously recirculated.

Materials and Methods

The study was carried out in a 1.8 m × 2.4 m walk-in growth chamber (EGC Inc., Chagrin Falls, OH). Plants were grown in eight trapezoidal-shaped PVC plastic trays, approximately 18 and 41 cm wide on the ends, 84 cm long, and 5 cm deep (Fig. 1). This design was chosen so that trays can ultimately be placed in a circular arrangement currently used in a plant Biomass Production Chamber (BPC) at NASA's Kennedy Space Center (Prince *et al.*, 1987).

A complete nutrient solution (Table 1) was continuously pumped from the same reservoir to each tray at a flow rate of approximately 500 ml min^{-1}. The wide end of each tray (41-cm side) was elevated 2 cm to allow passive (gravity) flow of the solution to the narrower end where it was returned

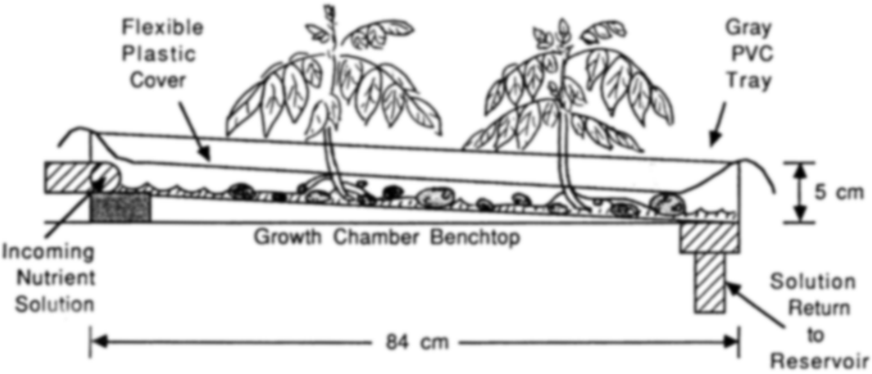

FIG. 1. Diagram of PVC plastic trays used for growing potatoes with nutrient film technique (NFT). Nutrient solution entered at the elevated end of the tray at about 500 ml min^{-1} and flowed to the lower end for return to a reservoir and recirculation.

TABLE 1.—*Starting nutrient solution used to grow potatoes in a recirculating nutrient film technique (NFT).*

Major Elements	Concentration	Minor Elements	Concentration
	(mmol L^{-1})		(μmol L^{-1})
N	7.5	Fe	60.00
P	0.5	B	19.00
K	3.0	Mn	3.70
Ca	2.5	Zn	0.32
Mg	1.0	Cu	0.13
S	1.0	Mo	0.04
		Cl	7.50

to the reservoir. The total water volume of the reservoir approximately equaled 80 liters. Supplying each tray from the same reservoir presented a potential problem in that any event occurring in one tray (*e.g.*, leaching of root exudates) would affect all other trays (Jarrett and Chanter, 1981), but assured that any perturbations in solution electrical conductivity, pH, and elemental balance would affect all trays equally. Because only nitrate-nitrogen was used in the nutrient solution (Table 1), solution pH tended to increase during periods of rapid growth and heavy nitrate uptake (Marschner, 1986). To balance this, an automatic pH controller was used to add 0.39M HNO_3 (concentrated acid diluted to 2.5%, v/v) to continuously maintain the pH near 6.0. Each day, deionized water was added to the reservoir to replenish water taken up (transpired) by the plants. Twice each week, nutrients were replenished by adding stock solutions to the reservoir (Table 2). The composition and amounts of stock solutions added were based on preliminary NFT growouts relating total water use and nutrient

TABLE 2.—*Nutrient replenishment of recirculating solution used in nutrient film technique (NFT) for potatoes.*

Salt	Stock Concentration (mol L^{-1})	Biweekly Replenishment (ml of stock added per liter of water lost from system)
$Ca(NO_3)_2$	1.0	1.5
KNO_3	1.0	5.2
KH_2PO_4	1.0	0.9
$MgSO_4$	1.0	0.7
Fe-EDTA	0.009	5.0
MicroNutrients	(1)	1.8

[1] Final micronutrient concentrations and ratios according to Tolley-Henry and Raper (1986).

solution conductivity (C.L. Mackowiak, unpublished) and micronutrient levels used in related controlled environment studies (Tolley-Henry and Raper, 1986). Elemental levels in the solution were determined weekly using atomic absorption spectroscopy.

Each tray was covered with a sheet of opaque polyethylene plastic, white on the top surface and black on the bottom surface. Nodal-propagated sterile culture plantlets of cvs Denali and Norland were transplanted to holes cut into the plastic cover so that approximately one half of each plantlet's stem was beneath the surface of the plastic and the roots were kept continually wet. Plantlets of each cultivar were spaced either one or two per tray. All plantlets were covered with glass beakers for the first 72 hrs to reduce transplant shock (Wheeler and Tibbitts, 1986).

To establish rapid shoot development and ground cover, the chamber was maintained under continuous light (*i.e.*, 24-h photoperiod) and a constant temperature (17.3 C ± 0.7 C) for the first 28 days (Wheeler *et al.*, 1986). On day 29, chamber conditions were changed to 12-h photoperiod with a matching thermoperiod (19.7 C ± 0.2 C light/16.0 C ± 0.4 C dark) in an attempt to promote rapid tuber initiation. On day 57, conditions were switched back to continuous light and constant temperature (17.9 C ± 0.4 C) to maximize the photosynthetically active radiation (PAR) on the plants. Lighting throughout the study was provided by 30 VHO Vitalite fluorescent lamps. Canopy-level photosynthetic photon flux (PPF) levels were measured weekly and averaged 244 μmol m^{-2} s^{-1} (±26 μmol m^{-2} s^{-1}) for all the trays throughout the study. Relative humidity averaged 67% (± 5%) throughout the study, while CO_2 levels were not controlled and ranged from approximately 350 to 450 μmol mol^{-1}.

Forty-five days after planting, twine fences were positioned to support shoot growth and confine a group of four trays to a total area 1.6 m^2. This allotted an average of 0.4 m^2 area per plant for trays with single plants, and 0.2 m^2 area per plant for trays with two plants.

All plants were harvested at 112 days (16 weeks). Stems and leaves were separated and oven-dried at 70°C for at least 48 h for dry weight determination. Tubers were separated as either larger or smaller than 2.5 cm average diameter, counted and weighed. A 100-g sample of tissue was taken from four typical tubers from each tray and dried to determine percent dry weight. This percentage was then applied to the total fresh weight from each tray to estimate total tuber dry weight yield. Harvest index was calculated as the ratio of tuber dry weight to total plant dry weight. Following harvest, samples of shoot and tuber tissue were analyzed for proximate nutritional composition (Nutrition International Inc., East Brunswick, NJ).

Results and Discussion

Shoot growth progressed rapidly under the continuous light for the first 28 days but periodic inspections of the stolons showed that few tubers had initiated on either cultivar during this time. Within two weeks after switching to a 12-h photoperiod at 28-days-age, tuber initiation was progressing rapidly for both cultivars. By 70-days-age, shoot growth had slowed substantially but tuber bulking continued. After 112 days, nearly all Norland leaves and approximately 75% of the Denali leaves had died back or were showing senescence. Such extensive senescence of shoots under growth chamber conditions was somewhat surprising, particularly with a late cultivar such as Denali. Previous controlled environment studies with Norland plants have lasted up to 147 days without complete senescence (Wheeler and Tibbitts, 1987). The changes in photoperiod and temperature used in this study may have strongly favored tuber development and consequently hastened shoot senescence.

At final harvest (112 days), Denali plants produced the greatest yield in terms of tuber and total plant fresh weight (fwt) and dry weight (dwt) (Table 3, Fig. 2). No difference was apparent between the one- and two-plant Denali trays, with both spacing treatments yielding approximately 2.8 kg per tray. In contrast, two-plant trays of Norland yielded approximately 25% more than one-plant trays (2.6 vs 2.1 kg). This would indicate that under the radiation level of this study, a spacing of 0.4 m^2 per plant for Norland was wasteful, *i.e.*, spacing was too wide. For Denali plants, the more vigorous shoot growth (Table 3) appeared to compensate for wider plant spacing. For each cultivar, the number of tubers larger than 2.5 cm diameter was greater from two-plant trays than from one-plant trays. The high harvest index (tuber dwt/total plant dwt) values, 77% to 80%, in conjunction with shoot senescence would indicate that all the plants of both cultivars were heavily induced to tuberize under the conditions chosen.

TABLE 3.—*Yield data from potatoes grown in nutrient film technique for 112 days.*

Cultivar	Spacing	2 Shoot Dwt	Root+ Stolon Dwt	No. of Tubers >2.5cm	Total Tuber Fwt	Total Tuber Dwt	Total Plant Dwt	Harvest Index
	(plants per tray)	(g per tray)	(g per tray)		(g per tray)	(g per tray)	(g per tray)	(%)
Denali	1	154	13	36	2849	666	833	79.8
Denali	2	141	15	50	2834	636	792	80.3
Norland	1	104	6	26	2078	364	474	76.8
Norland	2	127	8	40	2600	457	592	77.1

[1] Data represent averages of 2 trays per spacing treatment except for "Norland 1" where only one tray was used.

[2] Each tray provided 0.4 m^2 of growing area, allotting 0.4 m^2 per plant for one-plant trays and 0.2 m^2 area per plant for two-plant trays.

FIG. 2. Tuber yields from Denali (light-colored) and Norland (dark-colored) plants grown for 112 days in nutrient film technique (NFT). Each tray contained two plants.

Proximate nutritional analyses of the dried tuber tissue by cultivar are shown in Table 4 (no comparisons were made between spacing treatments). Denali tubers contained slightly higher carbohydrate levels than Norland tubers (79% vs 75%), but Norland tubers had higher protein levels (11.4% vs. 8.7%). These values for protein were similar to levels in tubers grown in solid media under controlled environment conditions (Wheeler and Tibbitts, unpublished) and are within the range of levels reported for tubers from typical field-grown plants (Duke and Atchley, 1986). Thus the NFT system had no peculiar effects on tuber development and nutritional composition for the parameters measured.

Although tuber yields were comparable to those reported in other controlled environment studies (Wheeler and Tibbitts, 1986, 1987), some of the tubers showed superficial injury not reported in studies using solid media. This injury was characterized by a cracked periderm, and in some instances with surrounding blackened tissue. The injury was confined to approximately the outer 5 mm of tissue and did not penetrate deep into the tuber. Several of the affected tubers showed encrustation of a lighter col-

TABLE 4.—*Proximate nutritional composition of potato tubers grown in nutrient film technique (NFT).*

Cultivar	Protein[1]	Fat	Ash	Crude Fiber	Carbo-hydrate	Calculated Calories[2]	"Bomb" Calories[3]
	(%)	(%)	(%)	(%)	(%)	(kcal/g)	(kcal/g)
Denali	8.75	0.42	5.86	1.26	79.18	3.56	3.8
Norland	11.43	0.46	6.85	1.75	75.15	3.50	3.8

[1] Calculated as total N X 6.25.

[2] Calculated as protein and carbohydrate containing 4 kcal g^{-1} and fat containing 9 kcal g^{-1} and fat containing 9 kcal g^{-1}.

[3] Determined by bomb calorimetry.

ored material near the injured area, which we presumed to be salt accumulation from nutrient solution evaporating from the surface of the tuber. Thus the injury may have resulted from a "salt burn," but this is speculative. If this is the case, it may be critical in future NFT studies with potatoes to ensure that tubers are sufficiently rinsed by flowing nutrient solution during development or that the area beneath the tray or container covers is well sealed to prevent solution evaporation. It is likely that lifting of the covers for regular inspection of tuber development may have aggravated this injury by accelerating evaporation.

System (plant) water use in the study increased with time until plants were approximately 40-days-old and canopy "ground cover" of the trays was complete; water uptake then appeared to decrease with plant age and onset of senescence (Fig. 3). The changes in photoperiod and temperature at 29 and 57 days had little effect on water uptake. Approximately 9 liters (L) of water had to be added to the solution reservoir each day during the period of greatest use (ca. 40 days). Over the entire 112-day growing period, a total of 709 L of water was added to sustain the 3.2 m^2 of plants, or 2.0 L m^{-2} day^{-1}. If one scales this rate upward to the size of 1 hectare (ha), twice the area of a life support farm that might be needed for a large lunar colony (Salisbury and Bugbee, 1985), approximately 20,000 L of water would be required each day to sustain a recirculating NFT system with potatoes.

Daily additions of a dilute HNO_3 to maintain nutrient solution pH at 6.0 increased during the period of rapid shoot growth (10- to 25-days-age) and then declined as shoot growth slowed and tuber bulking increased (Fig. 4). The period of high acid additions likely reflects a period of rapid anion (*i.e.*, nitrate) uptake (Marschner, 1986), but no specific nitrate analyses were taken to verify this. A total of 6604 ml of 0.39 m HNO_3 were added for the 3.2 m^2 over the 112-day growing period, or 18.4 ml m^{-2} day^{-1}

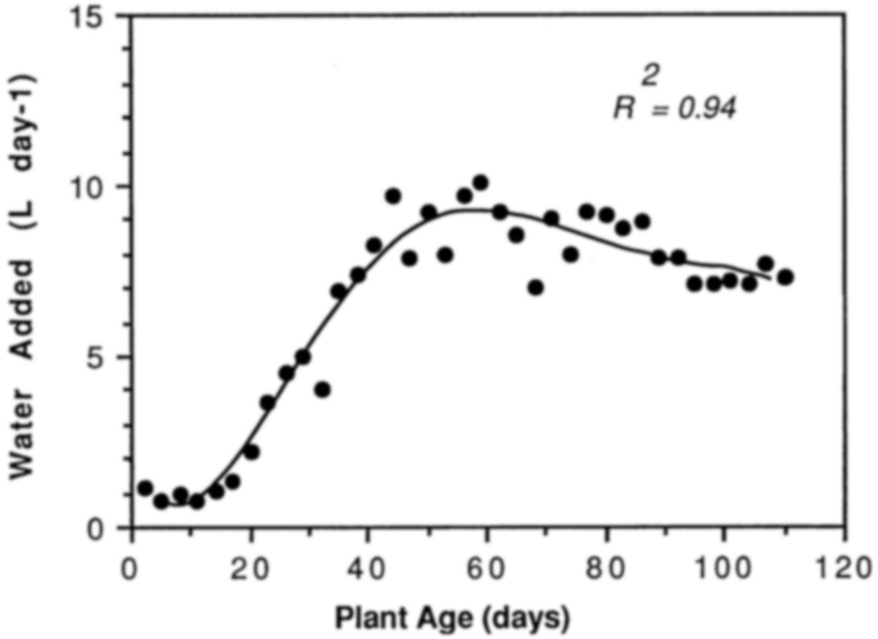

FIG. 3. Volume of water added to the reservoir of NFT system to compensate for evapotranspiration. Total reservoir volume was approximately 80 liters. Data represent 24-h averages over three-day intervals. The entire system supported an area of 3.2 m^2 of potatoes with complete ground cover occurring ca. 40 days.

(7.2 mmol m^{-2} day^{-1}. Extrapolating these measurements to an area of 1 ha indicates that approximately 184 L of 0.39 HNO_3 (72 mol HNO_3), or the equivalent 4.6 L of concentrated HNO_3 would be required each day to maintain pH in a recirculating NFT using exclusively NO_3-nitrogen.

The best tuber dwt yields obtained in this study would equate to a productivity of 10.2 g m^{-2} day^{-1} for Norland and 14.9 g m^{-2} day^{-1} for Denali. Yields of Norland plants grown in pots of peat-vermiculite and with a similar total level of photosynthetically active radiation equaled 15.1 g m^{-2} day^{-1} (Wheeler and Tibbitts, 1987); thus NFT appears to be a viable approach to growing potatoes in controlled environments, particularly with further refinements in cultural techniques and hardware. Because NFT systems have limited chemical buffering capacity and low water volume in the rooting zone, system alarms and back-up hardware (*e.g.*, water pumps) are essential to prevent catastrophic failures. However, the features of water recycling, low total water volume, and the capability to closely control solution nutrient concentrations and pH in NFT are highly desirable with regard to a closed life support system in space where resources will be severely limited and costly to provide.

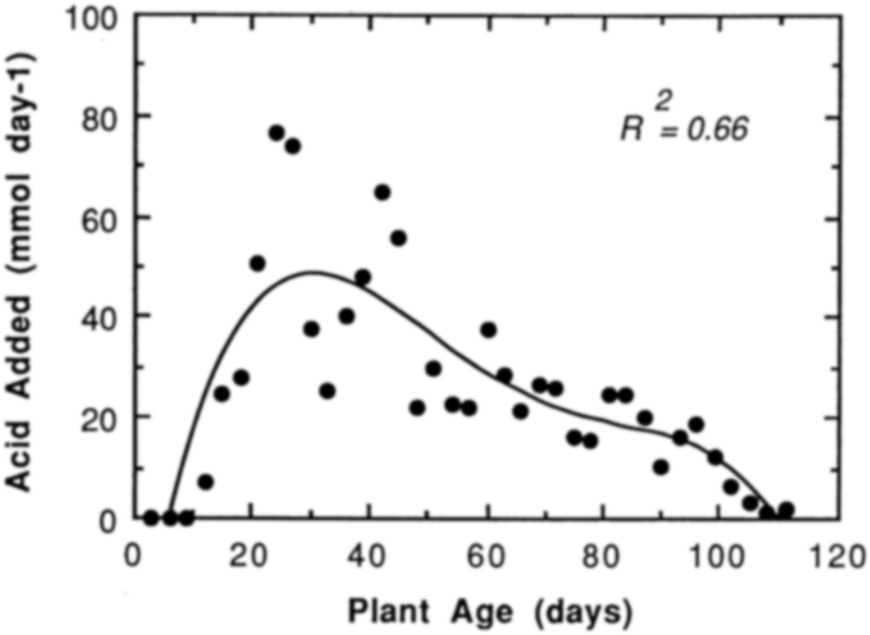

FIG. 4. Amount of nitric acid added to NFT system reservoir to maintain pH of 6.0. Total reservoir volume was approximately 80 liters. Data represent averages over three-day intervals. Only nitrate-nitrogen was used in the nutrient solution, thus pH tended to rise during periods of rapid growth and heavy nitrate uptake (Marschner, 1986).

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