N88-12269

UTILIZATION OF POTATOES IN BIOREGENERATIVE LIFE SUPPORT SYSTEMS

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ABSTRACT

Data on the tuberization, harvest index, and morphology of 2 cvs of white potato (Solanum tuberosum L.) grown at 12, 16, 20, 24 and 28°C, 250, 400 and 550 µmol s^{-1} m^{-2} photosynthetic photon flux (PPF), 350, 1000 and 1600 µl l^{-1} CO_2 will be presented. A productivity of 21.9 g m^{-2} day^{-1} of edible tubers from a solid stand of potatoes grown for 15 weeks with continuous irradiation at 400 µmol s^{-1} m^{-2}, 16°C and 1000 µl l^{-1} CO_2 has been obtained. This equates to an area of 34.3 m^2 being required to provide 2800 kcal of potatoes per day for a human diet. Separated plants receiving side lighting have produced 32.8 g m^{-2} day^{-1} which equates to an area of 23.6 m^2 to provide 2800 kcal. Studies with side lighting indicate that productivities in this range should be realized from potatoes. Glycoalkaloid levels in tubers of controlled-environment-grown plants are within the range of levels found in tubers of field grown plants. The use and limitation of recirculating solution cultures for potato growth is discussed.

BACKGROUND

The white potato, Solanum tuberosum L., is one of eight plant species identified in the U.S. for primary consideration as useful crops /1/ for a biogenerative or controlled ecological life support system (CELSS). The others are wheat, rice, peanut, soybean, sweet potato, sugar beet and lettuce. Potatoes are unique among these crop species in that the edible portions of the plant develop as tubers below the soil surface on underground, horizontally-growing stems. The potato was selected for inclusion in a space life support system because of several desirable characteristics.

Productivity: Foremost among these characteristics of the potato is its very high productivity of digestible food per unit area per unit time, a level that is as high as any other species in this selected group except sugar beets (Table 1). The calculations shown in Table 1 were based on maximum harvested yield data for different countries of the world /2/ utilizing a typical field growing period and adjusting for the water content, for the portion of the produce that is not eaten, and for the portion that is not digestible /3/.

Harvest index: Of significant importance in a CELSS is the fact that potatoes have a very high harvest index, 80% (Table 1). This means that 80% of the dry matter accumulated by a mature potato plant is allocated to tubers and only 20% to the inedible stems, leaves and roots. Thus, the expenditure of energy required for recycling the inedible portions of a potato plant will be significantly less than for species that have a lower harvest index. Typically the harvest index of species for which vegetative tissues are consumed is high (eg. potato, lettuce, sweet potato), whereas the harvest index of species for which reproductive tissues, as seeds and fruits (e.g. wheat, rice, peanuts), are consumed is usually significantly less. It is important to note, however, that the harvest index does not necessarily represent the total usable portion for most crops, as a portion of the harvested product is often discarded in the form of husks or peeling; this unusable portion can be as high as 25% for rice and peanuts. Also, the harvested portion that is consumed includes a fraction of non-digestible dry matter. This is highest in sugar beets and lettuce.

The edible portion of potatoes, the tubers, consists mostly of the carbohydrate, starch. However about 9% of the dry weight of tubers is protein. These proteins have a reasonable balance of all required amino acids and are high in lysine compared to most of the other selected crops. In fact, the quantity of protein present in potatoes is sufficient to satisfy the total protein requirement of a person if all the dietary energy requirements were met with potatoes.

TABLE 1 Productivity of various food crops proposed for utilization in CELSS.

English Name	Crops Latin Name	Field Production ($g\ m^{-2}$)	Growing Period (days)	Edible or Usable Portion (%)	Water Content (%)	Digestible Food Edible Portion (%)	Digestible Food Dry Weight ($g\ m^{-2}\ day^{-1}$)
Wheat	Triticum sativum	738	100	95	14.0	98.0	5.91
Brown Rice	Oryza sativa	789	110	75	14.4	89.5	4.12
Sugar Beets	Beta vulgaris	6440	160	100	75.0	76.8	7.26
Peanuts	Arachis hypogaea	360	150	75	5.0	93.8	1.61
Soybeans	Glycine max	283	140	95	10.0	94.5	1.64
White Potatoes	Solanum tuberosum	5492	150	90	79.8	85.9	5.72
Sweet Potatoes	Ipomea batatas	2186	120	90	70.6	86.8	3.92
Crisphead Lettuce	Lactuca sativa	3474	60	90	95.1	81.1	2.32

Culinary: Potatoes, along with all of the selected crops, are palatable and acceptable to most people. This contrasts to certain other food species that are highly productive but which are not as palatable for a significant proportion of humans.

Preparation: Potatoes require a minimum of processing to make them useful as foods thus making it possible to minimize the "kitchen" facility and energy requirements in a CELSS unit. The tubers are ready for kitchen use when harvested from the plants. They also can be prepared in many different ways so that they can be utilized in nearly every meal. For example, potatoes can be eaten raw, boiled, baked, fried, microwaved, french fried, scalloped or processed into chips, sticks and puffs. In addition, a flour can be made from potatoes and used in many ways. Potatoes can be stored for periods up to 6 months as fresh tubers or for longer periods as a frozen or dried product.

Information: There is extensive knowledge on the cultural requirements and physiology of potatoes with entire books dedicated to this in many different countries, and there are collections of diverse germ plasm available from the plant introduction stations in many countries from which diverse genetic traits can be obtained to breed potatoes best suited for controlled environment production. Furthermore, potatoes can be easily maintained from stem cuttings in sterile tissue culture, and less than 0.2 m^2 of space would be required to maintain planting stock and transplants to grow the food (energy and protein) requirements for one person. Thus disease-free uniform plant stock can be easily propagated and maintained for an operational CELSS.

RESEARCH

Production: Potatoes have been grown successfully in controlled environments under electrical lighting, without any sunlight, by researchers on numerous occasions. We have utilized cool white fluorescent lamps exclusively to provide normal growth and development of potato plants. The following graph (Figure 1) depicts the production obtained from potato plants of the Norland cultivar in a controlled environment room under continuous irradiation at a PPF (photosynthetic photon flux) of 400 $\mu mol\ s^{-1}\ m^{-2}$ ($400\ \mu E\ s^{-1}\ m^{-2}$) and at 16°C temperature. Individual plants were maintained in 38-liter containers filled with a potting mixture and watered four times each day with nutrient solution /4/. Each plant was constrained by a wire netting that provided 0.2 square meters of cross-sectional area. Successive harvests demonstrated that tuber production continued to increase until the last harvest at 147 days but that the productivity in grams $m^{-2}\ day^{-1}$, as shown by the values in parenthesis, peaked at 126 days (32.46 g $m^{-2}\ day^{-1}$) although the productivity was essentially level from 105 days to 147 days. In an operational CELSS, there would likely be an advantage to maintaining plants for as long a growing period as possible to reduce the frequency of planting and harvesting operations.

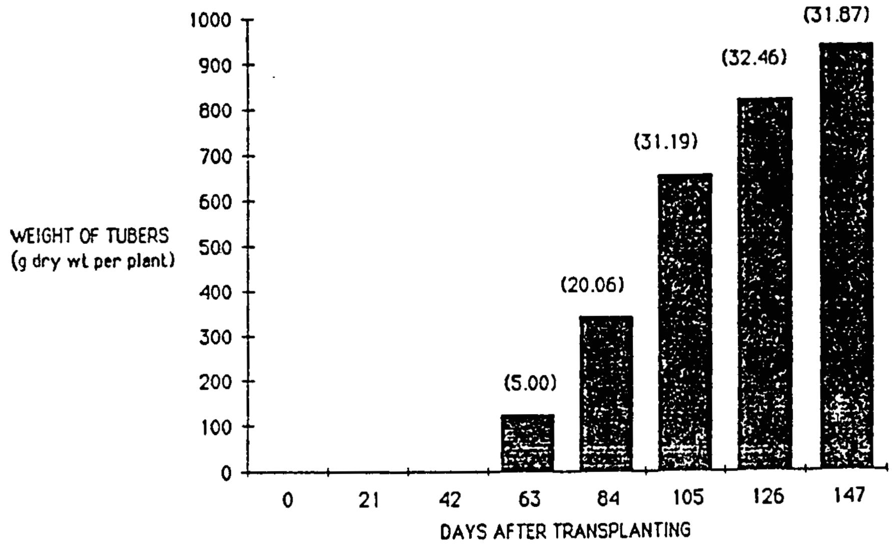

Fig. 1. Tuber production of Norland potato plants grown at 16°C and 400 µmol s^{-1} m^{-2} PPF. Plants were individually confined within a 0.2 m^2 fenced area. Values in parentheses are g dry matter m^{-2} day^{-1}.

<u>Light interception</u>: Under normal growth, potatoes very quickly begin branching and spread out to form a solid stand. When plants are spaced on 50-cm centers, there is total light interception by 6 weeks after planting. After this time, there is essentially no light penetration through a solid canopy as shown in Figure 2 and thus irradiation is maximally utilized from 6 weeks on. Because the leaves of potato tend to be nearly horizontal, they are capable of intercepting light very effectively. Figure 3 shows that when potato plants were grown in a solid stand under a 12-hr photoperiod, a leaf area index of two (i.e. two layers of leaves above a unit area of ground) effectively intercepted over 90% of the incident radiation. This characteristic permits potatoes to grow well and maintain high productivity at relatively low irradiance levels.

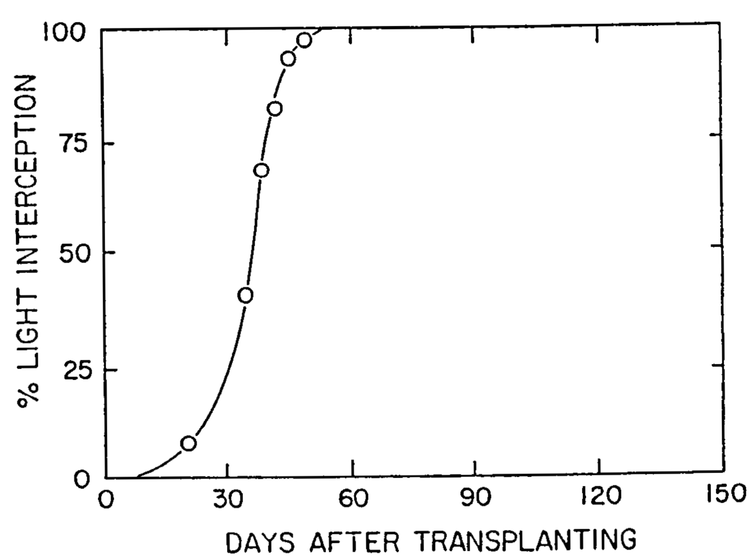

Fig. 2. Light interception by potato plants as measured at soil surface midway between pots spaced 0.5 m apart.

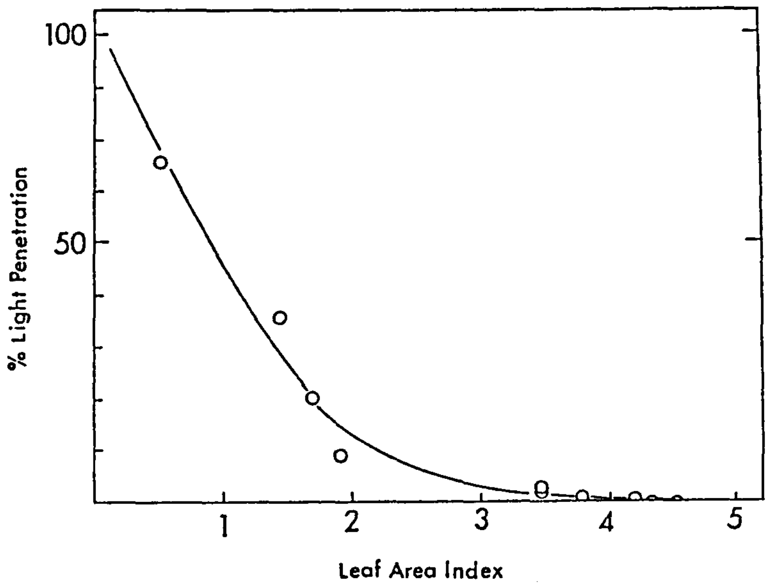

Fig. 3. Penetration of light through a canopy of potato leaves as a function of leaf area index (i.e. area of leaves above a unit area of ground). Potato plants were grown under a 12-hr photoperiod using cool white fluorescent lighting.

Lighting: It has long been accepted and demonstrated that short photoperiods, e.g. less than 12 hours, encourage tuberization of potatoes, however we have found that continuous irradiation (24 hr) will provide tuberization if sufficient light intensity is provided. A photosynthetic photon flux level (PPF) of 400 µmol s^{-1} m^{-2} maintained continuously, provided 60% more tubers than with the same level maintained for a 12-hr period and 12-hr dark each day (Table 2). There was evidence at the 6-wk harvest that tuber development began slightly sooner with 12 hr irradiation but in all succeeding harvests, tuber production was significantly greater under continuous irradiation than under 12 hr irradiation. Even the harvest index of plants grown under continuous irradiation was high and essentially the same as under 12-hr irradiation (Table 2). Note that the tuber production under continuous irradiation is only about 50% greater than under 12 hr irradiation, yet the total photosynthetically active radiation received each day with continuous lighting is double the amount obtained under the 12-hr photoperiod. This suggests that there is greater irradiant energy conversion efficiency with the 12-hr photoperiod, or in other words, there is a greater dry weight increase for a given quantity of irradiation.

TABLE 2 Dry Weight and Harvest Index of Norland Potato Plants Grown Under Different Irradiance Durations.

Light (hrs)	Dark (hrs)	Dry Weight: Tubers (g per plant)	Dry Weight: Leaves (g per plant)	Dry Weight: Stems (g per plant)	Harvest Index (%)
12	12	617	134	9	80
24	0	937	167	37	81

16°C at PPF level 400 µmol $s^{-1}m^{-2}$ for 21 weeks

Evidence that long photoperiods do suppress tuberization was seen in an experiment comparing 400 µmol s^{-1} m^{-2} PPF for 12-hr with 200 µmol s^{-1} m^{-2} for 24 hr in which the same total amount of irradiation was provided over a 24-hr period. There was essentially no tuberization under the continuous light treatment and good tuberization with a 12-hr light treatment (Table 3). However, this long photoperiod suppression of tuberization can be overcome by increasing the irradiance level from 200 to 400 µmol s^{-1} m^{-2}, as shown in the middle treatment of this table. It is noteworthy that when total plant growth was compared between 400 µmol s^{-1} m^{-2} for 12 hrs and 200 µmol s^{-1} m^{-2} for 24 hrs for these 6-week old plants, there was less total dry weight and poorer energy conversion efficiency with the 12-hr treatment (Table 3).

TABLE 3 Dry Weight of Norland Potato Plants Grown at Different Irradiance Durations and Levels.

Irradiance		Dry weight per plant	
Duration (hrs)	Level of PPF ($\mu mol\ s^{-1} m^{-2}$)	Total biomass (g)	Tubers (g)
12	400	53	12.2
24	400	125	19.6
24	200	80	0.4

20°C for 6 weeks

A significant concern in the use of continuous irradiation is that only about one-half of the cultivars we have tested will develop and tuberize normally. This includes the cultivars Norland, Russet Burbank, Denali, Atlantic, and Snowchip. Other cultivars have become chlorotic after two weeks of growth, producing small leaves and greatly stunted growth. This injury response has been seen with Kennebec and Superior cultivars. A partial chlorosis and stunting also has occurred with Norchip cultivar.

Our research to date has not established the most useful level of irradiation for potatoes. Limited studies with continuous irradiation at 550 $\mu mol\ s^{-1}\ m^{-2}$ have provided little tuber or total dry matter gains over 400 $\mu mol\ s^{-1}\ m^{-2}$, thus we are hypothesizing that 400 $\mu mol\ s^{-1}\ m^{-2}$ when given continuously, is close to a maximum useful level. However, we suspect that higher irradiance levels may be beneficial if irradiation is provided for shorter photoperiods.

Temperature: Tuberization is very dependent on the temperature under which the plants are grown. Tuberization is stimulated by cool temperatures and shown to be maximum between 16 and 20°C (Table 4). At 28°C no tubers formed on the plants. The total dry weight followed a similar pattern as tuberization. The stem length of plants was significantly shorter with decreasing temperatures and consequently, the harvest index was highest and most desirable at the coolest temperatures.

TABLE 4 Dry Weight, Stem Length, and Harvest Index of Norland Potatoes Grown Under Different Temperature Levels.

Temperature (°C)	Dry Weight: Tubers (g per plant)	Dry Weight: Total Plant (g per plant)	Stem Length (cm)	Harvest Index (%)
12	73	123	18	59
16	123	209	37	59
20	96	186	48	51
24	2	151	74	1
28	0	116	94	-

Continuous PPF of 400 $\mu mol\ s^{-1} m^{-2}$ for 8 weeks.

Carbon dioxide: Elevation of carbon dioxide concentrations has been found to be only of marginal benefit to potato plants when grown under continuous irradiation at 400 $\mu mol\ s^{-1}\ m^{-2}$. There has been little or no gain in tuber dry weight either in short-term studies of 8 weeks (Table 5) or long-term studies of 15 to 18 weeks. We have obtained some evidence that the late-maturing cultivar, Russet Burbank, derived some benefit from CO_2 increases but no evidence that the early-maturing cultivar, Norland, benefits from CO_2 increases. The lack of enhanced growth from CO_2 enrichment suggests that we have approached the physiological limit of the growth capacity of the potato plant under the continuous irradiance levels of 400 $\mu mol\ s^{-1}\ m^{-2}$.

TABLE 5 Tuber Dry Weight of Potato Plants Grown Under Different Carbon Dioxide Concentrations.

Concentration	Tuber Dry Weight Norland cv	Tuber Dry Weight Russet Burbank cv
($\mu l\ l^{-1}$)	(grams per plant)	
400	85	88
1000	74	103
1600	81	105

20°C at PPF level of 400 μmol $s^{-1}m^{-2}$ for 8 weeks

Productivity: The tuber production from our research studies can be utilized to calculate the area and lamp power required to provide the average energy requirements, 2800 kcal per day, for one person living in a space colony. Knowing that one gram of dry weight of potatoes contains 3.73 kcal of energy, then 750 grams of dry weight of potato would be required for one person per day. We have obtained a production of 21.9 g m^{-2} day^{-1} from a solid stand of potatoes. Thus the area required for one person to fulfill energy and protein requirements is 34.3 m^2. If the production from the single plants in separate cages (32.8 g m^{-2} day^{-1}) could be obtained from a solid stand, then only 23.6 m^2 would be needed to meet the requirements for one person. We feel that this latter figure is a realistic estimation of space requirements needed, and only requires that lighting systems be designed to provide irradiation to all sides of the plant.

In a commercial plant growing facility in the United States, a light level of 400 μmol s^{-1} m^{-2} requires 304 lamp watts m^{-2} using high pressure sodium lamps. Using this efficient conversion, (23.6 m^2 x 304 wm^2) approximately 7.2 kw of electricity would be required per person.

Stem length: Potato growth in a life support system will likely be constrained by the total volume of the growing modules to be utilized. A concern in use of potatoes for space systems is that potatoes have a tendency to grow long stems. Stems can be in excess of a meter in length on certain cultivars and this extension is encouraged by elevated temperatures, long photoperiods, and low light levels. It has been found that early-maturing cultivars tend to have shorter stems than late-maturing cultivars apparently because the early-maturing cultivars stop producing shoot growth when tuberization is vigorous wheras late-maturing cultivars continue active shoot growth during tuberizataion. We have seen that caged plants receiving side lighting exhibit less stem elongation. This has encouraged us to develop a lighting system to provide supplemental irradiation just above the soil level on each side of the plants using 1500 mA CWF lamps. Plants with side lighting developed short main stems and branches yet produced the same total dry weight and similar tuber dry weight as plants grown without side lighting. We are pursuing further studies using within canopy lighting to determine whether this procedure will not only reduce stem length, but also irradiate the plants more efficiently and reduce the space required for fulfilling production needs.

Recirculating nutrient: Significant effort has been directed toward developing a means of growing potatoes in recirculating nutrient solutions. These systems are being studied to provide effective nutrient recycling and to examine the possibility of harvesting individual tubers as each matures and thus hopefully maintaining plants in a continuously productive state. Potato plants grow well in many different types of recirculating systems but in most systems we have studied, plants failed to tuberize normally, exhibiting delayed tuber initiation and sometimes producing many but only small tubers.

The most successful system that we have utilized involves filling a 90 cm long X 60 cm wide and 20 cm high polyethelene tray with either calcined clay particles (arcillite) or sphagnum moss and slanting the tray so that nutrient solution (300 ml min^{-1}) can be added along one end of the tray and recirculated through holes on the opposite end of the tray (Figure 4). This approach produced rapid and good tuberization and studies are currently underway to determine the minimum depth of calcined clay required for effective tuberization in these trays. If a depth of less than 3 cm is effective, the potential for studying continuous tuber harvesting would be available.

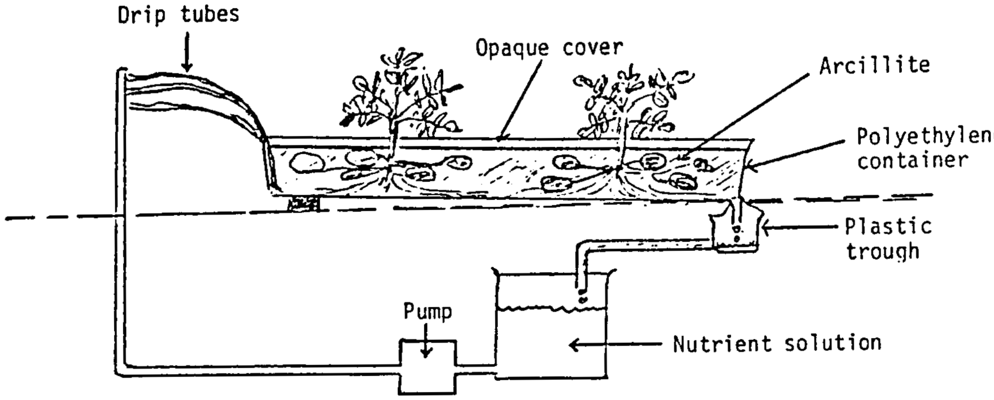

Fig. 4. Diagram of recirculating tray culture system for potato production. Tray filled with particles of calcined clay (arcillite) and fed continously at one end with 300 ml min^{-1} of nutrient solution.

In other studies when solution was recirculated through containers filled with nutrient solution and the plant roots and lower stem immersed, tuber initiation and development was greatly slowed. When the solution level was lowered to expose the lower stem area, tuberization was still slowed. However, when the solution level was lowered and the area around the lower stem filled with sphagnum moss, tuberization was essentially normal.

To date, mist culture systems ("aeroponics") also have not provided effective tuberization. A mist system was developed with a spinning impellor located at the level of the tuber forming stems, which continuously atomized solution onto the underground stems and the root systems (Figure 5). The solution was collected in the base of the misting compartment for recirculation. Although tuberization was generally slowed it was possible to stimulate tuber development if the system was stopped for a sufficient period to slightly wilt the plants or by complete removal of nitrogen from the recirculating solution.

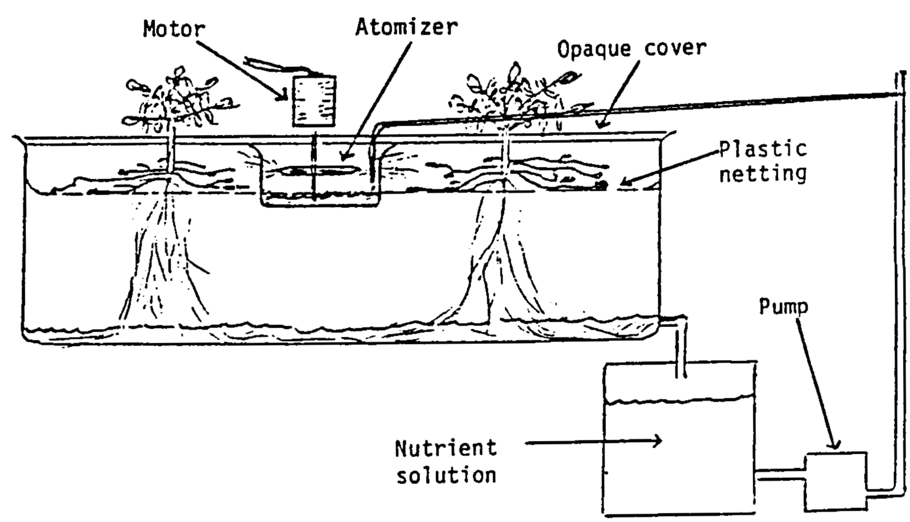

Fig. 5. Diagram of mist culture system developed for potatoes utilizing a spinning atomizer with recirculating nutrient solution.

Glycoalkaloid levels: A significant concern in our research effort has been the possibility that the unique growing procedures utilized in maximizing production for CELSS would increase the toxic glycoalkaloid level in the tubers. The glycoalkaloids, chaconine and solanine, are prevalent in potatoes and are known to vary in concentrations depending upon the conditions during growth /5/. Thus sample tubers from all experiments are regularly analyzed for these glycoalkaloids and we are gratified to report that we have found no levels under any growing conditions studied that exceed the average levels found in field potatoes. In our studies the levels found have been 0.03 to 0.07 mg per gram fresh weight for chaconine and 0.02 to 0.05 mg per gram fresh weight for solanine.

Summary: The research to date with potatoes suggests that this crop has a significant place in an operational CELSS and can be utilized either alone or in combination with other food crops, to fulfill a significant portion of the energy and protein requirements of humans in space. The high potential productivity of nutritious tubers, easy propagation, and the high harvest index of the potato plant make it a particularly strong candidate. Thus potatoes, along with other useful crops, can serve a vital role in a life support system ... to feed astronauts, provide needed oxygen, and remove carbon dioxide.

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