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PROXIMATE COMPOSITION OF CELSS CROPS GROWN IN NASA'S BIOMASS PRODUCTION CHAMBER

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ABSTRACT

Edible biomass from four crops of wheat (*Triticum aestivum* L.), four crops of lettuce (*Lactuca sativa* L.), four crops of potato (*Solanum tuberosum* L.), and three crops of soybean (*Glycine max* (L.) Merr.) grown in NASA's CELSS Biomass Production Chamber were analyzed for proximate composition. All plants were grown using recirculating nutrient (hydroponic) film culture with pH and electrical conductivity automatically controlled. Temperature and humidity were controlled to near optimal levels for each species and atmospheric carbon dioxide partial pressures were maintatined near 100 Pa during the light cycles. Soybean seed contained the highest percentage of protein and fat, potato tubers and wheat seed contained the highest levels of carbohydrate, and lettuce leaves contained the highest level of ash. Analyses showed values close to data published for field-grown plants with several exceptions: In comparison with field-grown plants, wheat seed had higher protein levels; soybean seed had higher ash and crude fiber levels; and potato tubers and lettuce leaves had higher protein and ash levels. The higher ash and protein levels may have been a result of the continuous supply of nutrients (e.g., potassium and nitrogen) to the plants by the recirculating hydroponic culture.

INTRODUCTION

The US National Aeronautics and Space Administration (NASA) has been conducting tests for a number of years to examine the potential of higher plants for producing food, oxygen, and clean water for life support systems /1-6/. All of these studies were conducted in controlled environments with lighting, temperature, humidity, water, and mineral nutrient supplies carefully regulated to promote rapid growth and high yields. Unfortunately, little information is available from these studies on the nutritional composition of crops grown under controlled environment conditions. Information is available on the nutritional value of field-grown crops /7/ that might be used for CELSS modeling, but crops in field settings are often exposed to suboptimal and fluctuating temperatures, humidities, and nutrient and water availability, as well as insect pests and diseases. Thus it is likely that plants grown in controlled environments with minimal stress may differ in nutritional composition from plants grown in the field.

As part of the Breadboard Project at Kennedy Space Center, FL, USA, we have been conducting tests with candidate CELSS crops in a closed Biomass Production Chamber (BPC). The intent of these tests was to gather biomass-production and gas-exchange data of CELSS crops grown on a large scale (20 m^2) in a closed system. As a part of these studies, proximate nutritional analyses of the harvested biomass have been conducted on a regular basis. We report here the results of these proximate analyses to provide a starting information base for the nutrient composition of candidate crops grown under controlled environment conditions that might be used in a CELSS.

MATERIALS AND METHODS

All plants were grown in the Biomass Production Chamber (BPC) at the Kennedy Space Center, FL, USA. The chamber is a cylindrical, steel vessel 3.7 m in diameter and 7.5 m high that was formerly used for hypobaric testing during the Mercury Project. The chamber provides four vertically-stacked annular growing shelves for supporting plant culture trays, with each shelf providing approximately 5 m^2 of growing area. Lighting is provided by 96, 400-W high pressure sodium (HPS) or metal halide (MH) lamps (24 lamps per shelf), with maximum photosynthetic photon flux (PPF) at the tray level (60 cm below the lamp barrier) being about 700 $\mu mol\ m^{-2}\ s^{-1}$ for HPS lamps and 500 $\mu mol\ m^{-2}\ s^{-1}$ for MH lamps. All plants were grown in trapezoidal shaped plastic culture trays (~0.25 m^2 area each) with water and nutrients provided using a recirculating nutrient film technique with a complete nutrient solution and nitrate as the sole source of nitrogen /8/ (TABLE 1). Nutrient solution pH was controlled between 5.5 and 6.0 using automatic additions of dilute (0.4 M) HNO_3. Water uptake by the plants was replenished by adding deionized water to the nutrient solution reservoirs each day and solution electrical conductivity was maintained near 0.12 S m^{-1} using automatic additions of a concentrated stock solution (TABLE 1).

TABLE 1. Elemental composition of starting nutrient solution and replenishment concentrate solution used for plant growth sutides in NASA's CELSS Biomass Production Chamber.

Element	Starting Solution	Replenishment [1] Concentrate
	(mM)	(mM)
NO_3-N	7.5	75.0
PO_4-P	0.5	7.5
K	3.0	68.0
Ca	2.5	7.5
Mg	1.0	9.8
S	1.0	9.8
	(µM)	(µM)
Fe	50 [2]	199
B	9.50	87
Mn	7.40	68
Zn	0.96	8.8
Cu	1.04	9.5
Mo	0.01	0.1

[1] *The values listed represent concentrations of the replenishment concentrate used for the majority of studies. This solution was added to the working nutrient solution to maintain an electrical conductivity of 0.12 S m^{-1}. Slight variations in the concentrations of specific nutrients were made over the course of the studies*

[2] *Initial Fe concentration for all wheat studies was 100 µM.*

Wheat (*Triticum aestivum* L. cv. Yecora Rojo) plants were grown from 77 to 86 d using long photoperiods (20-h or 24-h) with relatively high PPF (500 to 750 $\mu mol\ m^{-2}\ s^{-1}$). Heads were separated from shoots at harvest and oven dried at 70°C for at least 48 h. Following drying, seeds were threshed from the heads and ground through a 2-mm mesh screen using a Wiley mill. Soybean (*Glycine max* (L.) Merr. cv. McCall) plants were grown from 90 to 97 d using short photoperiods (10-h or 12-h) with high PPF (500 to 800 $\mu mol\ m^{-2}\ s^{-1}$). Pods containing the seeds were removed from plants at harvest and oven dried at 70°C, after which seeds were removed and ground. Lettuce (*Lactuca sativa* L. cv. Waldmann's Green) plants were grown for 28 d using a 16-h photoperiod with moderate PPF (300 $\mu mol\ m^{-2}\ s^{-1}$). Lettuce heads were harvested, oven dried at 70°C, and ground for analysis. Potatoes (*Solanum tuberosum* L. cv. Norland or Denali) plants were grown for 90 or 105 d using a 12-h photoperiod and high PPF (650 to 900 $\mu mol\ m^{-2}\ s^{-1}$). Tubers were harvested and subsamples oven dried at 70°C and ground for analysis. Additional details on environmental and horticultural conditions for the different crops can be found in Wheeler et al. /5,6,9/.

Ground materials from each study (approximately 100 g per sample) were packaged in polyethylene bags and shipped to a commerical laboratory (Nutrition International, Dayton, NJ, USA) for total proximate analysis. Laboratory procedures involved dividing the samples into three subsamples for redundant measurements. Proximate analyses followed standard AOAC procedures /10/ and included the following: moisture by vacuum oven (AOAC method 934.01); ash by muffle furnace (AOAC method 900.02), protein by Kjeldahl nitrogen (AOAC method 981.10), crude fiber by digestion and gravimetric technique (AOAC method 962.09); fat by ether extraction and acid hydrolysis (AOAC methods 920.39 and 922.06); and carbohydrate calculated by difference. Dietary energy equivalents were calculated by assigning 4 kcal g^{-1} carbohydrate, 4 kcal g^{-1} protein, and 9 kcal g^{-1} fat.

RESULTS AND DISCUSSION

Results for proximate analyses of wheat seed, soybean seed, lettuce leaves, and potato tubers grown in the BPC are shown in TABLE 2. Soybean seed had the highest protein and fat (oil) content, and consequently the highest energy content of any of the plant tissues, whereas potato tubers and wheat seed had the highest carbohydrate. Lettuce leaves had the highest ash content, and soybean seed and lettuce leaves had the highest crude fiber.

TABLE 2. Proximate composition of crops grown in NASA's CELSS Biomass Production Chamber. [1]

Crop / Study	n[2]	Protein	Fat	Ash	Crude Fiber	Carbo-hydrate[3]	Energy Content
		(%)	(%)	(%)	(%)	(%)	(kcal/g)
Wheat / 881	2	18.4	3.2	2.0	2.5	73.3	3.98
Wheat / 891	1	20.9	3.1	2.1	3.2	71.6	3.94
Wheat / 892	2	20.1	3.3	1.9	2.8	72.3	3.95
Wheat / 931	2	17.0	2.9	2.0	2.4	75.7	4.05
Ave.		19.1	3.1	2.0	2.7	73.2	3.98
Soybean / 891	2	36.3	19.3	7.0	9.5	28.0	4.30
Soybean / 901	2	36.4	18.5	7.6	8.8	28.8	4.27
Soybean / 902	2	36.2	21.9	7.5	14.9	19.3	4.26
Ave.		36.3	19.9	7.4	11.1	25.4	4.26
Lettuce / 901	1	24.6	8.2	22.4	11.1	33.6	3.07
Lettuce / 902	2	30.2	4.1	22.0	11.1	32.7	2.88
Lettuce / 911	2	27.2	4.5	21.8	9.4	37.0	2.97
Lettuce / 921	4	27.8	1.6	21.1	9.7	39.8	2.85
Ave.		27.4	4.6	21.8	10.3	35.8	2.94
Potato / 911[4]	2	16.0	0.2	7.2	1.4	75.2	3.67
(Denali)	2	13.1	0.3	8.1	1.8	76.7	3.61
Potato / 912	4	18.1	0.7	9.1	3.3	67.9	3.53
Potato / 921	4	14.2	1.4	6.6	2.4	75.5	3.71
Potato / 931	2	14.5	0.7	6.8	2.5	75.6	3.76
Ave.		15.2	0.7	7.6	2.3	74.2	3.66

[1] *All data express on a dry-mass basis*

[2] *n = number of 100-=g samples analyzed; each sample was divided into three sumbsamples for replicate analyses by Nutrition International Inc., Dayton, NJ, USA.*

[3] *Carbohydrate values do not include crude fiber.*

[4] *Cv. Norland used for all studies except for study 911, which used cv. Norland and cv. Denali plants.*

A comparison of the controlled environment-grown plants from the BPC with data from field-grown plants /7/ shows that the composition of plants from both environments was roughly similar, with the following exceptions: Protein for wheat seeds, lettuce leaves, and potato tubers and ash for soybean seeds, lettuce leaves, and potato tubers were higher in the BPC plant tissue than in field-grown plants (Fig. 1). In addition, crude fiber of soybean seeds from the BPC was higher than field grown tissue. Carbohydrate (not including crude fiber) was lower in all species in BPC tissue in comparison to field-grown tissue.

Several explanations might be offered for these differences: 1) The field data were collected from a range of cultivars (genotypes), which might have slightly different genetic traits than the cultivars used in the BPC. In past studies with soybean and potato we have noted differences in proximate composition between cultivars; for example, cv. Pixie soybean seed typically has higher protein levels than McCall seeds /11/. 2) Because the BPC plants were grown hydroponically with solutions in which the electrical conductivity was maintained constant at 0.12 S m^{-1}, they likely had much higher levels of nutrients available than the field-grown plants. This may have resulted in luxuriant uptake of some nutrients, particularly potassium and nitrogen, which might increase ash and protein levels, particularly in vegetative tissue. Direct elemental analysis of lettuce and wheat leaves from these studies showed that

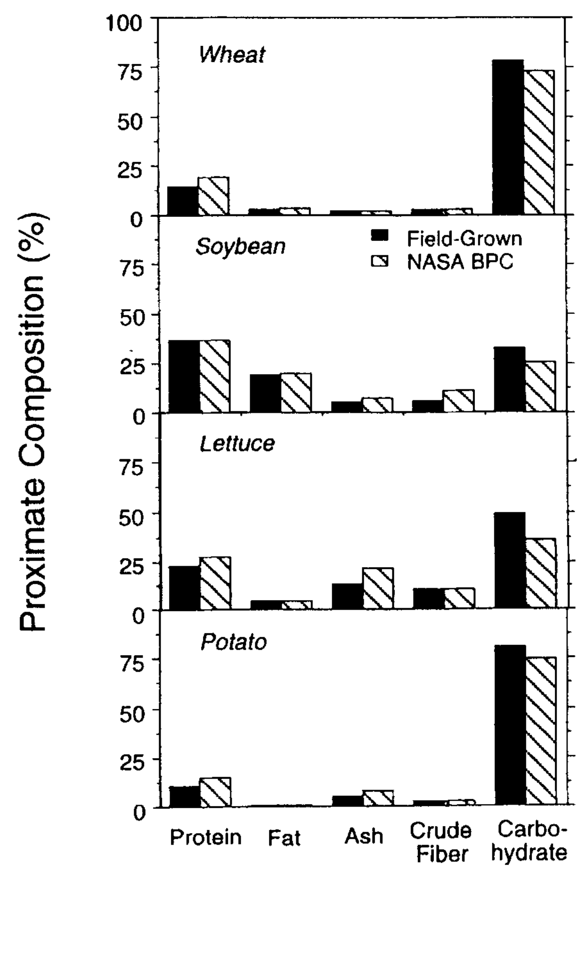

Fig. 1. Average proximate composition of wheat seed, soybean seed, lettuce leaves, and potato tubers grown in NASA's Biomass Production Chamber compared with values of field-grown plants /7/.

potassium levels were indeed very high, which would account for the high ash values /5,6/. Because a standard Kjeldahl method was used to estimate tissue protein, any nitrate in the tissue may have inflated protein estimates /12/. Vegetative tissue such as lettuce leaves are known to accumulate nitrate /13,14/ and this can be increased by applying high level of nitrate fertilizer /14/. 3) The BPC plants were grown at carbon dioxide (CO_2) partial pressures nearly three times higher than those in the field (100 Pa vs. 35 Pa). In previous studies /11/ we have noted that increasing the CO_2 caused an increase in soybean seed crude fiber, which may explain the higher fiber levels noted in these studies in comparison with field grown plants.

CONCLUSIONS

Analysis of CELSS crops grown in the controlled environment of NASA's Biomass Production Chamber (BPC) suggest that there were no fundamental differences in proximate nutritional composition in comparison with field-grown plants. However, ash and protein values tended to be higher in the BPC plant tissue, which may have been a result of the luxuriant nutrient uptake by the hydroponically-grown BPC plants. Whether this poses a concern in terms of human diet needs further study. If human nutritional problems are foreseen from diets high in ash and protein, methods for controlling excessive nutrient uptake by the plants might be explored. This could include selection of low nutrient accumulating cultivars and/or the use of leaner, i.e., less nutrient-rich solutions for growing plants.

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