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Nutritional characteristics and biomass production of Chenopodium quinoa grown in controlled environments

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**Nutritional Characteristics and Biomass Production of *Chenopodium quinoa*
Grown in Controlled Environments**

A Thesis

Presented to

The Faculty of the Department of Biological Sciences

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Masters of Science

by

Greg Schlick

December, 2000

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ABSTRACT

Nutritional Characteristics and Biomass Production of *Chenopodium quinoa* Grown in Controlled Environments

by Greg Schlick

This thesis defines the characteristics of *Chenopodium quinoa* grown under controlled-environment, hydroponic conditions. Proximate composition, lipid, amino acid, vitamin, and mineral analyses were conducted on both seed and leaf tissue. Preliminary trials on 10 cultivars were conducted in a greenhouse to determine the proper cultivar for growth chamber trials. Optimal lighting conditions for maintaining short stature while preserving a high seed yield included short day length (8 h) and high irradiance ($1800 \mu\text{mol m}^{-2} \text{s}^{-1}$). The controlled-environment production of quinoa yielded harvest indices similar to the highest reported from the field. Including the other edible portions of the plant would increase the harvest index to greater than 90%. Seed and leaf protein content was exceptionally high (20.9%). The high protein concentration, unique amino acid composition, high mineral and vitamin content, versatility in preparation, and potential for greatly increased yields in controlled environments could make quinoa a useful crop for controlled-environment production and for further consideration as a field crop.

NOMENCLATURE

AOAC	Association of Official Analytical Chemists International
BV	biological availability
FAO	Food and Agriculture Organization of the United Nations
GLC	gas-liquid chromatography
HDL	high density lipoprotein
HI	harvest index
HPLC	high pressure liquid chromatography
HPS	high pressure sodium
ICP	inductively coupled plasma
LDL	low density lipoprotein
NASA	National Aeronautics and Space Administration
NEG	nitrogen efficiency for growth
NRC	National Research Council
PAR	photosynthetically active radiation
PER	protein efficiency ratio
PPF	photosynthetic photon flux
RDA	recommended daily allowance
RH	relative humidity

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Nutritional Characteristics and Biomass Production of *Chenopodium quinoa* Grown in Controlled Environments

INTRODUCTION

We face the challenge of finding and developing new commercial crops for the world food market. Approximately 20,000 species of plants have edible parts, but only about 100 have been brought to an advanced agronomic level (Vietmeyer, 1990). It is important to diversify our crops, as our current dependence on a few major ones makes us vulnerable to food shortage. New crops may provide reasonable productivity and reliability as well as nutritional and medicinal benefits.

Controlled-environment agriculture offers a number of benefits to developing new crops. In controlled environments, the environment is optimized in order to maximize productivity. There is no restriction on geographical location, and the risks associated with the introduction of a foreign species to a region are reduced. As population grows and agricultural land diminishes, controlled environments become more feasible and cost effective. Plants respond differently in controlled environments than in the field, so it is important to identify the most productive set of environmental parameters in order to maximize yield and nutritional properties.

Chenopodium quinoa Willd. has enormous potential, especially in controlled-environment agriculture. Significant increases in yield and nutrient content in many crop species are attainable by growth in controlled environments (Bubenheim, 1991). Because of the significant food value associated with quinoa, the feasibility of controlled-environment culture was investigated. This paper summarizes efforts to select appropriate cultivars of quinoa for controlled-environment production and to determine optimal growing conditions for increased edible yield while maintaining or increasing the nutritional component.

General Characteristics and Agronomic Uses of Quinoa

Quinoa is a member of the goosefoot family (Chenopodiaceae), which includes sugar beets, Swiss chard, spinach, and Lamb's quarters. Quinoa is found in severe environments, such as high mountain plains (most of which exceed 3,600 m in elevation) and alkaline salt flats, as well as in relatively moderate habitats, such as fertile valleys and moist coastal forests. It is a diet staple in the high regions of the Andes, because corn and wheat cannot compete at these high altitudes (Abrahms, 1988; Risi and Galway, 1984).

Quinoa is thought to have originated in the high mountain plains of Peru and Bolivia in the South American Andes (Cusack, 1984). It was the staple of the Inca Empire for many centuries. It has been cultivated in Peru, Chile, Bolivia, Ecuador, and Argentina for some time and more recently has been cultivated in the United States and Europe. In many areas of South America, but especially in the Andes, quinoa seeds are used to make flour for biscuits and cakes, added directly into soups, eaten as a breakfast cereal, and even used to make a very popular fermented drink (*chicha blanca*). The seeds have a mild, pleasant taste and are easily prepared. They are most often cooked like rice, producing a texture similar to cooked barley. The fresh leaves and tender shoots of the plant are eaten raw in salads or cooked and eaten as a vegetable. The young sprouts can also be added to salads or eaten plain. With the increasing availability of quinoa, many unique cooking methods are being developed (Quinoa Corp., Torrance, CA; Eden Foods, Clinton, MI; Arrowhead Mills, Hereford, TX).

Seed yield of quinoa is typically low under traditional farming conditions (450–900 kg ha⁻¹) for several reasons. The harvesting and processing techniques are time consuming and, in the current areas of cultivation (in South America), there is a

need to produce no more than that which can be used. With improved commercial and experimental harvesting and processing techniques, yields greater than 2,200–3,300 kg ha⁻¹ have been achieved (Cusack, 1984).

To better assess the productivity of quinoa, it has been studied extensively in the field in Bolivia, Chile, and Peru and to a much lesser extent in Europe and North America. Field studies indicate that quinoa maintains an unusually high protein content and a good balance of the essential amino acids (Ahamed *et al.*, 1998; Becker and Hanners, 1990; Gonzalez *et al.*, 1989; De Bruin, 1964). However, significant variation in nutrient composition has been reported among varieties. Bubenheim (1991) has found the use of controlled, hydroponic environments decreases variability while increasing yields and nutritional value in wheat, soya, and other crops. Initial experiments with growing quinoa in controlled-environment, hydroponic systems proved successful (Schlick and Bubenheim, 1993). Quinoa exhibited rapid growth, high seed yield, and good nutritional composition.

MATERIALS AND METHODS

Variety/Cultivar Selection for Controlled-Environment Agriculture

Cusack (1984) summarized a classification system devised by Tapia (1979) that identified four distinct groups: valley quinoa, altiplano quinoa, salt flat quinoa, and sea level quinoa. Valley quinoa, found at altitudes of 2,100–4,000 m, grows to 2.5 m in height and matures in 5–7 mo. Altiplano quinoa, found at altitudes higher than 3,600 m, achieves a height of 1.0–1.8 m and matures in 4–5 mo. Salt flat quinoa inhabits salt-deposit areas between 3,000–3,600 m in elevation and grows taller and matures more slowly than the altiplano group. Sea level quinoa inhabits low altitudes, grows to 1.0–1.8 m in height, and matures more slowly than the altiplano group.

Ten different accessions of quinoa were examined in greenhouse trials for potential use. The genotypes evaluated in the initial screening were *QL3* and *QH3* from Cambridge University, *CO407 X Isluga* and *CO407 Heat Tolerant Population 1* from Colorado State University, *Real*, *Sajama* and *Cochabamba 250* from Bolivia, *Blanca de Junin* from Peru, and *Faro* and *Temuco* from Chile. For both greenhouse and growth chamber studies to follow, the primary selection criteria for advancement of the genotypes in the selection process were canopy height, biomass production, seed yield, harvest index, and life cycle duration. For determination of these properties, growth, development, and morphology were characterized over time. Individual plants in the communities were measured weekly for height, branch number, internode length, and leaf area index. The number of days to floral initiation, number of days to flowering, duration of seed fill, and number of days to maturity were also determined. At harvest, the plants were oven dried at 60°C to a uniform weight before dry mass was determined for seeds, leaves, stems, and roots and a yield analysis performed. In addition, six plants per treatment, *i.e.*, two plants per tray, were randomly removed and analyzed separately. The detailed analysis included the number, size, and mass of each branch and head, and the total number of seeds per head. Following weighing, plant parts were milled through a 40-mesh screen.

Because of the general lack of experience with the hydroponic culture of quinoa, the preliminary trials in greenhouses focused on providing an appropriate nutritional regime. Following several seed-to-seed trials, the candidate accession list was trimmed to four for assessment in growth chambers: *Real*, *CO407 X Isluga*, *CO407 Heat Tolerant Population 1*, and *QL3*. The other cultivars exhibited extreme growth habits under all conditions and were eliminated early in the process. A detailed characterization of the crop physiology of quinoa grown under controlled environment, hydroponic production was pursued using the four cultivars. A ranking was developed

through a series of production studies while general responses to environmental factors such as photoperiod, nutrient composition, planting density, and temperature were determined. The top ranking cultivar, *QL3*, was the first to be advanced for further growth chamber trials.

Greenhouse Growing Conditions

Plants grown in the greenhouse using a recirculating, deep-film hydroponic system were maintained at $21^{\circ}\pm 3.0^{\circ}\text{C}$. Carbon dioxide concentrations were maintained at $1000 \pm 200 \text{ mmol mol}^{-1}$ by a natural gas CO_2 generator and measured by a non-dispersive infrared CO_2 monitor (Horiba Instruments, model APBA-250E, Irvine, CA). The plants were grown under both long (12 h photoperiod) and short day (8 h photoperiod) conditions (average daily photon flux of 49.7 and $15.3 \text{ mol m}^{-2} \text{ d}^{-1}$, respectively). The hydroponic system consisted of twenty-four 14 L polypropylene tubs (38.1 x 50.8 cm) in each chamber. The nutrient solution was delivered through a distribution manifold inside each tub that uniformly delivered the water, dissolved oxygen, and nutrients to the root zone. A overflow pipe allowed the nutrient solution to return to the reservoir. The nutrient solution (Table 1) was maintained at a pH of 5.8, and the electrical conductivity was maintained at 0.50 mS during the first 20 days and then increased to 1.50 mS for the remainder of the experiment.

Growth Chamber Growing Conditions

The initial efforts to define the yield potential for quinoa in highly controlled environments were focused on a series of experiments designed to determine photoperiod and irradiance responses. Three nearly identical growth chambers (EGC Model M-12, Chagrin Falls, OH), each with approximately 0.8 m^2 of growing area, were modified to increase the number of environmental variables controlled and to

better maintain those conditions in the growth environment. The standard C-3 microprocessor (standard EGC control system) was removed and replaced with a Optomux analog and digital brain board (Opto 22, Opto), which supplied and received the input/output signal to and from a computer running Paragon 550 Control Software (Intec Controls Corp., Wapole, MA). The control package allowed precise and complete computer control for all the environmental parameters.

Table 1. Hydroponic nutrient solution for *C. quinoa*.

Nutrient	Seedling Solution Conc.	Standard Solution Conc.
$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$	0.5 mM	2 mM
KNO_3	0.5 mM	2 mM
KH_2PO_4	0.15 mM	0.6 mM
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	0.13 mM	0.5 mM
K_2SO_4	0.13 mM	0.5 mM
$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	2.5 μM	10 μM
$\text{FeCl}_3 + \text{HEDTA}$	11.3 μM	45 μM
$\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$	0.75 μM	3 μM
$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$	0.75 μM	3 μM
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	0.05 μM	0.18 μM
$\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$	0.02 μM	0.09 μM
H_3BO_3	0.5 μM	2 μM

The light source in the growth chambers consisted of six 400W HPS lamps and six 400W metal halide lamps, all on dimmer ballasts. The dimming ballast, which does not alter spectral quality (Bubenheim *et al.*, 1995a), helped to control irradiance levels. Long-wave radiation (>1000 nm) was filtered (to reduce the heat load in the chamber) through 2 cm of deionized water flowing over an acrylic barrier, leaving unaltered the transmission of photosynthetically active radiation (PAR). Lower PPF levels were attained by placing plastic light diffusers into the water bath, which reflected/refracted the desired amount of light away from the plants. The diffusers did not alter the spectral quality of the light entering the chamber. Spectral quality was measured with a

spectral radiometer (EG&G-Gamma Scientific, Model GS-4100, San Diego, CA). The PPF was measured at the top of the plant canopy twice weekly with a quantum sensor (Licor Instruments, Model LI-189, Lincoln, NE). The light levels were recorded and integrated and the integrated value was used to determine the distance the plants were moved by a mechanically adjustable rack. In addition, a quantum sensor (Licor Instruments, Model 190SA, Lincoln, NE) was kept at a constant level inside the chamber to allow proper integration between the control system and manual measurements. As the plants neared their maximum height, additional diffusers were added to the water bath to reduce the light. This also served to distribute the light more uniformly over the canopy as the plants neared the light source.

Relative humidity was maintained at $80 \pm 0.1\%$ by a humidity sensor (Viasala Instruments, Hummitter, Helsinki, Finland) located inside an aspirator box which controlled a dehumidification coil, an atomizing humidifier, and a heating coil. Temperature was maintained at $21^\circ \pm 0.5^\circ\text{C}$ by a platinum resistance thermometer (Hayashi Denkoh Co., Tokyo, Japan) located inside an aspirator box. The CO_2 level was maintained at $1000 \pm 10 \text{ mmol mol}^{-1}$ by injecting CO_2 from a large liquid CO_2 tank (Taylor-Wharton Cryogenics, Theodore, AL) that was gasified before entry into the chamber. The flow was regulated by a flowmeter and a solenoid valve. The CO_2 concentrations were continuously monitored and controlled by a non-dispersive infrared carbon dioxide monitor (Horiba Instruments, Irvine, CA).

The rootzone environment was designed the same way as in the greenhouse study. The nutrient solution was maintained in the same manner as in the greenhouse trials (Table 1).

Analysis of Nutritional Value

A total proximate analysis, mineral composition, and amino acid profile was determined for each of the separated tissues: roots, leaves, stems, and seeds. A fatty acid profile, carbohydrate profile, total starch content, ascorbic acid (vitamin C), thiamin (vitamin B₁), riboflavin (vitamin B₂), niacin (vitamin B₃), retinol (vitamin A), α -tocopherol (vitamin E), and β -carotene analysis were completed by Nutrition International, Inc., NJ, and the analytical laboratory at NASA/Ames Research Center.

Seed tissue analysis was completed after uniform air drying and removal of the pericarp. Leaf, shoot, and root tissues were analyzed by the following two protocols. First, tissue was collected after seed fill and oven dried until a uniform dry weight was obtained (InterMetro Industries Corp., C85-DVN drying oven, Hartford, CT). Secondly, tissue was collected 40 days from the day of planting and immediately placed in a lyophilizer (FTS Systems, Dura-top μ P, New Brunswick, NJ). Lyophilization allowed for a more accurate proximate, amino acid, fatty acid, and vitamin analysis of the leaf, stem, and root tissue.

Total proximate analysis measured moisture (remaining moisture after oven drying), protein, fat, ash, crude fiber, carbohydrate, and calories. Moisture was determined by vacuum oven drying and weighing, protein by Kjeldahl nitrogen, fat by ether extraction, ash by muffle furnace, and crude fiber by gravimetric digestion, all as described in the AOAC International Manual (1995). The remainder of the mass was assumed to be carbohydrate. Total dietary calories were determined by bomb calorimetry (AOAC, 1995). A nitrogen:protein conversion factor of 6.25 was used to calculate protein content (Souci *et al.*, 1994).

Amino acid analysis was completed by HPLC according to the Spectra-Physics Manual (1986). The fat-soluble vitamins (vitamin A and E and β -carotene) were analyzed utilizing column chromatography (AOAC, 1995). The water-soluble

vitamins, thiamin and vitamin C, were analyzed by a microfluorimetric technique, whereas niacin and riboflavin were quantified by a turbidometric technique using *Lactobacillus plantarum* and *L. casei*, respectively (AOAC, 1995). Fatty acid analysis was completed utilizing GLC (AOAC, 1995). The carbohydrate profile was determined by HPLC (AOAC, 1995). Total starch content was determined by the Boehringer Mannheim Enzymatic UV Test.

The elemental tissue and nutrient analysis was performed at UCLA by the Lab of Biochemical and Environmental Sciences, at the Cornell Nutrient Analysis Laboratories, and at the analytical laboratory at NASA/Ames Research Center. Approximately 10 g of tissue was collected from each plant part for elemental tissue analysis at time of harvest. In addition, approximately 30 ml of nutrient bathing solution was collected throughout the experiment to monitor nutrient uptake and availability. Tissue and nutrient solution samples were completed in triplicate. Tissue samples for mineral composition were randomly chosen from all tubs to minimize bias. Tissue analysis was conducted by arc-spectroscopy and the nutrient solution analysis by Inductively Coupled Plasma (ICP) (Ewing, 1985). In subsequent experiments, elemental sulfur concentrations in plant tissue and the nutrient solution were determined at NASA/Ames Research Center and at Nutrition International, Inc. (AOAC, 1995). These trials were conducted in the hydroponic greenhouse identical to the growing system that was used to determine cultivar selection.

RESULTS AND DISCUSSION

Growth Characteristics in Greenhouse, Hydroponic Culture

Quinoa (variety *QL3*) seeds germinated rapidly (within 24 h), and cotyledons appeared within 96 h of sowing. Within seven days, the first true leaves emerged, and

in approximately 20 days the shoots grew to about 25 cm in height. Shortly thereafter, rapid nutrient uptake occurred (as reflected in a decrease in the electrical conductivity of the hydroponic solution) and the growth rate of the shoot increased. Flowering began at approximately 25 days after sowing and continued for 30–40 days.

Hydroponic culture prevented plants from developing extensive root systems. While the roots branched significantly, the central tap root, on average, extended only 15 cm.

Variety/Cultivar Selection

It is critical for controlled-environment crops to meet certain criteria that include small canopy stature, high harvest index, and a favorable nutritional composition. While most of the cultivars examined exhibited a positive response to controlled-environment production in reference to harvest index and nutritional composition, many grew too tall for effective growth chamber work. Some achieved heights of 2.5 m. Of the cultivars examined, *Real* and *QL3* showed the greatest promise with respect to canopy stature, biomass partitioning, and seed yields. *Real* exhibited a reasonable height (60 cm) and maintained high seed yield under short-day conditions; however, under long-day conditions, it attained a height of 140 cm. The height of the *QL3* canopy was similar (58 cm) under short days and was the shortest (90 cm) of all the varieties tested under long-day conditions. Additionally, *QL3* branched little and consistently had the highest seed yield and harvest index under both long-day and short-day conditions, compared with the other varieties evaluated. The performance of *QL3* in controlled-environment production, as presented here, was equivalent to or surpassed the performance of other crops currently grown in controlled-environment agriculture. The canopy height, yield, biomass accumulation rate, life cycle duration, and harvest index were all appropriate for continued consideration of quinoa as a

controlled-environment agricultural crop. Greater definition of yield potential was, therefore, justified.

In controlled, hydroponic environments, it is possible to double yields obtained by traditional farming techniques by reducing the limitations imposed by suboptimal temperature, CO₂, water, and nutrient conditions (Bugbee and Monje, 1992). In controlled environments, higher planting densities, which can lead to higher yield, are possible due to proximity of the light source, higher irradiance levels, and modified day lengths. The optimal field planting density reported for quinoa is approximately 32 plants m⁻² (Johnson and Croissant, 1985). From our yield per unit area, harvest index, and biomass accumulation data, a planting density of approximately 130 plants m⁻² appeared to be optimal in terms of harvest index for hydroponic controlled-environment production (Table 2).

Table 2. Effect of planting density on height, harvest index, and shoot:root ratio of plants grown in hydroponic greenhouse conditions.

Number of Plants (m ⁻²)	Mean Height (cm)	Harvest Index ¹	Shoot-Root Ratio ²
320	69	0.13	0.14
220	67	0.11	0.14
190	67	0.11	0.13
160	63	0.12	0.13
130	62	0.22	0.13
100	63	0.21	0.12
50	70	0.11	0.07

¹ Harvest index is the partitioning of dry biomass between seed and vegetative parts.

² Shoot:root is the total shoot mass divided by the total root mass.

Photoperiod and Irradiance Effects on Canopy Height, Biomass Accumulation and Allocation, and Yield

QL3 responded favorably to a combination of high irradiance (1800 μmol m⁻² s⁻¹ instantaneous photon flux) and short day lengths (8 h photoperiod) (Tables 3-5). Increases in the photoperiod (12 or 16 h) while maintaining a constant high daily flux resulted in gains in total mass, shoot mass, and root mass (Table 3). However, the

increase in shoot mass was proportionally greater than that in root mass, as reflected in the shoot-root ratio and manifested in an increase in canopy height. Decreases in the instantaneous photon flux (1200 or 900 $\mu\text{mol m}^{-2} \text{s}^{-1}$) while maintaining a short photoperiod produced a similar height response, a desirable outcome for chamber-grown plants. These results suggested that the optimal lighting conditions for maintaining short stature of *QL3* included short days and high irradiance.

Other aspects of biomass production and allocation were affected by photoperiod and irradiance (Tables 3, 4). While long days (12 and 16 h) and low instantaneous photon flux levels (900 and 1200 $\mu\text{mol m}^{-2} \text{s}^{-1}$) promoted biomass increases of both the shoot (including seeds) and root (Table 3), the proportion of the seed mass compared to leaf mass was greater in the short photoperiod and high irradiance environments (Table 4). Plants grown under a short photoperiod had a relatively stable shoot:root ratio regardless of the irradiance conditions. Whereas the short photoperiod/high irradiance environment often produced the most desirable results for plant growth with respect to seed yield and harvest index, this high irradiance tended to increase seedling mortality. Therefore, it was preferable to reduce the irradiance to approximately 1000 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for the first 20-25 days, allowing the plants to accrue a significant biomass before ramping the irradiance up to 1800 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for the balance of the life cycle.

Table 3. Total biomass allocation in *C. quinoa* cv. *QL3* as influenced by photoperiod and irradiance in growth chambers.

Photoperiod (h)	Instantaneous Flux ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	Daily Flux ($\text{mol m}^{-2}\text{d}^{-1}$)	Canopy Height (cm)	Total Mass (g m^{-2})	Shoot Mass (g m^{-2})	Root Mass (g m^{-2})	Shoot-Root Ratio
8	1800	51.8	67	940	886	73	12.1
12	1200	51.8	75	1450	1314	136	9.7
16	900	51.8	86	1593	1444	149	9.7
8	1200	34.6	79	1336	1241	95	13.1
8	900	25.9	98	1546	1435	112	12.8

Table 4. Yield characteristics of *C. quinoa* cv. *QL3* as influenced by photoperiod and irradiance in growth chambers.

Photoperiod (h)	Instantaneous Flux ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	Daily Flux ($\text{mol m}^{-2}\text{d}^{-1}$)	Seed Yield (g m^{-2})	Leaf Yield (g m^{-2})	Harvest Index Seed Only	Harvest Index Seed&Leaf ¹
8	1800	51.8	529	193	0.57	0.77
12	1200	51.8	542	526	0.34	0.67
16	900	51.8	406	521	0.28	0.64
8	1200	34.6	494	432	0.37	0.69
8	900	25.9	557	499	0.36	0.68

¹ Harvest index is traditionally defined as the partitioning of seed versus vegetative yield. However, because the vegetative parts of *C. quinoa* are also edible, this value was calculated to define edible yield.

Most of the attention to this crop has been focused on the seed, but it is possible that the leaves provide an additional source of food and nutrition. If the edible leaves were added into the harvest-index calculation, the harvest index exceeded 80% (Table 4), indicating a very high edible proportion of the total crop biomass. Alternate harvesting techniques need to be examined, such as leaf harvest during the vegetative growth phase, to determine their effects, if any, on seed fill and yield.

Protein

Table 5 compares the proximate analysis values of quinoa grown in hydroponic culture with those grown in field trials, as summarized by Koziol (1992). For the sake of comparison, values have been corrected to show zero moisture content. Protein analysis data indicate very high values for quinoa seed. The increase in seed protein values found under hydroponic, controlled-environment conditions was likely due to increased nutrient availability found in recirculating hydroponic culture systems and to the absence of stress. While the total protein fraction is significant, the biological value of the protein is of greater importance. Lopez (1973) reported biological values of a "quinoa alone" diet to be similar to that of casein alone (considered a reference for biological value of proteins in mammals). Adding 20% quinoa flour to wheat flour increased the biological value of the wheat flour by 50% (Lopez, 1973). Mahoney *et al.* (1975) and Ranhotra *et al.* (1993) also concluded that the biological value, the protein efficiency ratio (PER, which is the ratio of body weight gain over the amount of protein consumed), and the nitrogen efficiency for growth (NEG, a method to determine the efficiency of converting absorbed nitrogen into carcass nitrogen) were very similar to those of casein, suggesting that the casein and quinoa proteins are equal in quality. Galwey *et al.* (1990) and Koziol (1992) summarized several studies on rats, cows, chickens, pigs, and humans and also found that the biological value, PER, and NEG of quinoa were as high as those of casein, indicating quinoa to be a high quality source of protein. A description of an amino acid analysis will follow the rest of the proximate analysis description in this paper.

Table 5. Proximate analysis of *C. quinoa* cv. *QL3* grown in controlled environment and compared with quinoa grown in a field environment (corrected for zero moisture).

Growing Conditions/ Organ	Component (%)				
	Protein ¹	Ash Fiber	Crude	Carbohydrate	Fat
Hydroponically Grown					
Seeds	20.9	4.9	2.8	78.5	5.5
Stems	11.2	7.2	27.2	57.8	0.7
Roots	13.3	15.0	26.3	74.8	0.4
Leaves	18.7	24.7	8.4	52.8	1.0
Field Grown ²					
Seeds	16.6	3.9	3.3	69.3	6.4
Leaves	21.9	19.1	13.7	35.0	3.8

¹Total Kjeldahl nitrogen.

² From Koziol (1992).

Leaves, stems, and roots also showed high concentrations of protein (Table 5), even with the onset of senescence. The leaf protein value obtained in the hydroponic study here represented a concentration approaching that in the seeds. The biological value of leaf protein is usually considered to be low, because its high fiber content makes it difficult to digest and because the amino acid composition is usually not in appropriate proportions for a human diet (Ostrowski-Meissner, 1983). The nutritional composition of seeds has been given the most attention. However, the leaves and stems of quinoa warrant further consideration. The leaves have a pleasant flavor, can be prepared raw in salads or cooked, and have concentrations of protein comparable to those reported for field-grown plants of quinoa (Table 5) and higher than that of spinach (Souci *et al.*, 1994).

Carlsson and Hanczakowski (1985) reported that the white leaf proteins extracted from quinoa have a relatively low biological value, possibly due to the high content of non-proteinaceous nitrogenous compounds. However, quinoa in combination with either soybean meal, fish meal, skim milk, or whey in a protein ratio of 1:1 increased the biological value of the protein in every case, except with the fish meal. Quinoa leaf

protein concentrates have high nutritive value, comparable to casein, and should be a good protein supplement for humans (Carlsson and Hanczakowski, 1985). Considering these findings, quinoa leaves may provide a good complement to other food proteins. This additional source of protein in the same plant may further increase the prospects of quinoa becoming attractive as a controlled-environment crop.

Ash

Ash levels in the hydroponically derived seeds and leaves were higher than those observed in field trials (Table 5). This discrepancy may be explained by the constant availability of all necessary nutrients in the hydroponic solution.

Crude Fiber

Crude fiber concentrations in seed were comparable under field and hydroponic conditions (Table 5). The fiber found in leaves of quinoa grown in controlled environments (8.4%) was considerably lower in content than that reported for field-grown plants (13.7%). The low concentrations in the leaves of the hydroponically grown quinoa were probably due to the diminished support requirements under the more hydric conditions and to the low stress environment of the growth chamber.

Carbohydrate

Carbohydrate concentrations in quinoa were greater under controlled environment in both seeds and leaves (Table 5). It is unclear why there was an increase in total carbohydrates; however, the carbohydrate forms and relative proportions were similar. Monosaccharide and polysaccharide concentrations were 2.51% and 3.17%, respectively, in the seed and leaf tissue of the chamber-grown quinoa. In these plants, approximately 59.1% and 47.5% (seed and leaf, respectively) of the carbohydrates were

in the form of starch. While starch granule size was not examined as part of this study, a number of authors have presented data for quinoa (Wolf *et al.*, 1950; Scarpeti de Briceno and Briceno, 1982; Atwell *et al.*, 1983; Varriano-Marston and DeFrancisco, 1984; Lorenz, 1990; Ahamed *et al.*, 1996; Prego *et al.*, 1998). Starch granule size ranges from 0.5 μm to 8.0 μm with most less than 1 μm (Ahamed *et al.*, 1996). Small starch granules provide unique commercial applications such as dusting starches used in cosmetics, candy, and rubber tire mold-releasing agents (Pomeranz, 1985). Starch granule size in corn and wheat is considerably larger (1-23 μm and 2-40 μm , respectively).

This starch granule size differential is important because gelatinization is related to the size of the starch granule; generally the smaller the starch granule the higher the temperature required for gelatinization (Kulp, 1973; Swinkels, 1985). However, quinoa, even with the small starch granules, initiates gelatinization at a temperature (56-58°C) similar to that of potato and wheat (58°C) and lower than that of rice and corn (68 and 62°C, respectively) (Koziol, 1992; Ahamed *et al.*, 1996). Additionally, small starch granules have been shown to destabilize dough (Kulp, 1973) and, combined with a low amylose content (11-12% for quinoa, 28% for wheat and corn), restrict quinoa's use in bread making (Koziol, 1992). Tapia (1979) and Romero *et al.* (1985) determined the limits of incorporation of quinoa flour for bread making to be 10-13% when combined with wheat. In other food products (pasta, tortilla chips), the percentage (30-40%) could be increased while maintaining an acceptable quality (Bacigalupo, 1973). The most unique feature of quinoa starch is its unusual freeze-thaw stability. Ahamed *et al.* (1996) reported that 60% of the water separated from 5% cornstarch after six freeze-thaw cycles, but there was no separation through eight cycles and only 12% after the ninth cycle in a 5% quinoa starch solution. It is unclear why

quinoa starch remains stable after numerous freeze-thaw cycles, but this may explain its effectiveness as a thickener in frozen food products (Ahamed *et al.*, 1996).

Lipids

Lipid concentrations in the seeds of hydroponically grown quinoa were at 5.5% (Table 5), which is fairly consistent with field levels (Cardoza and Tapia, 1979; Souci *et al.*, 1994). In the seed, 64% of the lipids were in the form of polyunsaturates, 17% monounsaturates, and the remainder saturated fatty acids (19%). The fatty acid composition (Table 6) was similar to that of soybeans (Simpson and Osbourne, 1978). The lipid content has been considered too low for oil extraction to be economical (Galwey *et al.*, 1990). However, the 5.5% concentration is greater than that in corn oil (3.8%), which has proven to be an economically valuable oil. The leaves and stem have a lipid concentration of 1.0% and 0.7%, respectively (Table 5). These concentrations were slightly higher than the values published by Koziol (1992) for field-grown quinoa and were approximately three times higher than in spinach (0.30%), a similar leafy vegetable. The primary essential fatty acid for humans, linoleic acid, is present in quinoa in concentrations suitable for the human diet (13.6% as a percentage of lipid fraction).

Linoleic acid is important in tissue formation and in the transport, breakdown, and excretion of cholesterol; it has been shown to be the precursor of a group of hormone-like compounds called prostaglandins, thromboxanes, and prostacyclins (Kadowitz *et al.*, 1975). Additionally, the concentration of linolenic acid (45.7% in the leaves) is significant. While linolenic acid has been shown to have essential fatty acid properties, it is not as effective as linoleic acid (Fiennes *et al.*, 1973), and it is not clear if linolenic acid is important in human nutrition (NRC, 1989).

Table 6. Fatty acid profiles of leaves of *C. quinoa* (as a percentage of lipid fraction) grown in controlled-environment, hydroponic solution and in a field environment.

Component		Hydroponic Leaves	Field-Grown ¹ Leaves
<i>Saturated fatty acids</i>			
Lauric	(C12:0)	0.1	0.2
Tridecylic	(C13:0)	0.2	—
Myristic	(C14:0)	0.6	1.1
Palmitic	(C16:0)	15.1	16.7
Margeric	(C17:0)	0.2	—
Stearic	(C18:0)	1.6	1.3
Arachidic	(C20:0)	1.6	3.5
Behenic	(C22:0)	0.6	3.6
<i>Monounsaturated fatty acids</i>			
Myristoleic	(C14:1)	0.2	—
Pentadecanoic	(C15:1)	0.7	0.2
Palmitoleic	(C16:1)	2.9	—
Heptadecanoic	(C17:1)	2.6	0.2
Oleic	(C18:1)	6.8	—
<i>Polyunsaturated fatty acids</i>			
Linoleic	(C18:2)	13.6	22.0
Linolenic	(C18:3)	45.7	38.9
Eicosadienoics	(all 20's)	0.8	—
Docosanoics	(all 22's)	0.9	—
Tetracosanoics	(all 24's)	0.3	—

¹ From Koziol (1992).

Amino Acids

Table 7 summarizes the amino acid composition of quinoa, accrued in multiple field trials (mainly in South America) and controlled-environment studies at NASA/Ames Research Center. Of primary interest was the high lysine value, which is uncommonly high for plants. Quinoa is also high in the sulfur-containing amino acids, methionine and cyst(e)ine. The levels of the other amino acids approached or exceeded the standards set by the Food and Agriculture Organization of the United Nations (FAO, 1989) (Table 7). Skimmed milk has been considered the standard food to assess protein quality for human nutrition. NASA has been working to develop a vegetarian-

based diet for long-term human exploration of space (Hoff *et al.*, 1982; Bubenheim, 1991; Cenci-McGrody and Stiller, 1997) and has needed to combine the

Table 7. Amino acid composition of quinoa seeds and leaves grown under controlled-environment, hydroponic conditions compared with wheat, soybean, skimmed milk, and with the amino acid requirements of humans.

Amino Acid	Content (g/100g protein)						Amino Acid Requirements ²
	Hydro-ponic Quinoa Leaves	Hydro-ponic Quinoa Seeds	Field Quinoa ¹	Wheat ¹	Soybean ¹	Skimmed Milk ¹	
Isoleucine	3.2	3.9	5.2	3.8	4.9	6.3	4.0
Leucine	5.6	6.4	6.7	6.8	7.6	9.7	6.7
Lysine	3.5	5.9	6.2	2.9	6.4	7.7	5.0
Phenylalanine	3.9	4.1	3.8	4.5	4.9	4.9	3.2
Arginine	4.0	9.4	7.9	4.8	7.2	3.7	2.0
Histidine	1.2	3.0	2.7	2.2	2.5	2.6	1.7
Alanine	3.9	4.0	4.4	3.8	4.3	4.0	-
Aspartic acid	8.0	9.0	8.1	5.3	12	8.3	-
Glutamic acid	14	15	14	27	18	23	-
Glycine	4.3	5.3	5.7	4.0	4.2	2.2	-
Proline	3.6	3.5	4.0	10	5.5	11	-
Serine	3.6	4.4	4.6	5.0	5.6	6.0	-
Tyrosine	2.6	3.2	3.1	3.1	3.5	5.0	3.2
Cyst(e)ine	0.6	1.0	1.4	2.3	1.5	0.9	1.3
Methionine	0.8	1.0	1.4	1.7	1.4	2.5	1.9
Threonine	3.5	3.5	4.1	3.1	4.2	4.6	3.4
Tryptophan	1.6	1.1	1.2	1.1	1.3	1.4	1.1
Valine	4.0	4.5	4.6	4.7	5.0	6.9	4.6

¹ From Souci, *et al.* (1994).

² From Scott (1986).

nutritional qualities of soy and wheat in order to obtain amino acid concentrations that meet the FAO requirements (Table 7). Among the species examined for amino acid composition, quinoa is unique in the plant kingdom in that it contains a well balanced composition of all the essential amino acids. NASA has had trouble designing meals that meet the nutritional needs of their crews; quinoa may provide the solution. In the hydroponic setting, most of the amino acid concentrations in quinoa seeds remained comparable to field-grown quinoa. However, there was a significant decrease in methionine and cyst(e)ine (29% reduction of each). Unfortunately, no amino acid

profile is available for this cultivar (*QL3*) grown under field conditions. However, this decrease was also observed in early trials with both *Real* and *CO407*. This decrease in cyst(e)ine and methionine may have been related to the time of harvest. Prakash and Pal (1998) reported changes in amino acid concentration (both increases and decreases in specific amino acids) in quinoa seeds during maturation of the seed. Alternatively, the decrease may have been a response to controlled-environment production (lack of stress), in which the formation of sulfur metabolites, often products of detoxification mechanisms, was suppressed. In addition, controlled-environment production may alter the ratio between the 2S (high sulfur; Brinegar et al., 1996) and the 11S (Brinegar and Goundan, 1993) seed storage proteins, resulting in a decrease in the sulfur-containing amino acids in the seed.

In additional experiments, suboptimal (<25 ppm) and superoptimal sulfur concentrations (300, 500, 700 ppm) were used in the hydroponic solution. No alteration in growth or vitality resulted, indicating that the sulfur concentration in solution had no noticeable morphological effect and probably no bearing on the internal concentration of these secondary metabolites in quinoa. Testing of specific stress responses, *i.e.*, metal toxicity, wind, and temperature in both root and shoot zone, are currently in progress to better understand the factors influencing sulfur-containing amino acid synthesis in quinoa.

Vitamins

While quinoa seed is not a good source of most vitamins, there are a few that were present in concentrations beneficial for human nutrition (Table 8). Vitamin E in hydroponically grown quinoa seed (10.04 mg/100 g) was present at substantially higher levels than in other grain crops. Thiamin (Vitamin B₁) was found in concentrations similar to those of other grain crops, and niacin (Vitamin B₃) was less concentrated but

still substantial in quantity. Vitamin E and niacin concentrations in hydroponically derived seed (Table 8) exceeded those of field-grown seed (Koziol, 1992). Some vitamin concentrations in leaves were substantially higher than in the seed (vitamin A 9328 IU/100 g, vitamin B₂ 2.85 mg/100 g). The vitamin A activity was also greater in controlled-environment quinoa than in the field-grown crop. The retinol equivalent (RE) for the controlled-environment grown quinoa leaves was 8905.9 RE/100 g. RE is

Table 8. Vitamin profiles of *C. quinoa* grown in controlled-environment, hydroponic solution *versus* a field environment.

Vitamin		Hydroponic		Field ¹	
		Seeds	Leaves	Seeds	Leaves
Vitamin A	IU/100 g ²	ND	9330	--	4128
Vitamin E	mg/100 g	10.04	9.63	5.37	1.30
Vitamin B1	mg/100 g	0.68	0.50	0.38	--
Vitamin B2	mg/100 g	0.26	2.85	0.39	--
Vitamin B3	mg/100 g	1.53	6.38	1.06	--
Vitamin B6	mg/100 g	ND	1.68	--	--
Vitamin C	mg/100 g	ND	69.40	4.00	--
Folic acid	mg/100 g	ND	1.16	--	--
β-carotene	IU/100 g	207	61,050	2.34	--

¹ From Koziol (1992).

² IU = international unit. Before the chemical nature of Vitamin A was known, it was necessary to express it in arbitrary biological units. One IU of Vitamin A is equivalent to 0.3 µg of crystalline Vitamin A, or retinol.

ND = not detectable.

a calculated value that corresponds to the active form of vitamin A in the body (retinol). Vitamin A (retinol) can be made in the body by converting precursors such as β-carotene to retinol (*i.e.*, 6 µg of dietary β-carotene is equivalent to 1 µg of dietary retinol). Therefore the total activity may be expressed as retinol equivalents, which correspond to the total retinol content plus one sixth the β-carotene content (Passmore, *et al.*, 1974). Koziol (1992) calculated that fresh field-grown quinoa leaves contained 1251 RE/100 g. In comparison, spinach (*Spinacia oleracea*) is considered to be good

sources of vitamin A and yields only 781 RE/100 g. Quinoa leaves may also be a valuable source of vitamins E, B₂, B₆, and C (Table 8).

Minerals

Quinoa has a high mineral content compared to most other major crops. Table 9 compares the mineral concentration of quinoa seeds and major cereal crop grains. For the most part, the minerals listed are substantially more abundant in quinoa than in these crops. Ballon *et al.* (1984) reported levels of P, Ca, K, Mg, Fe, Cu, and Zn to be higher in field-grown quinoa seeds than in barley, corn, or wheat grains. In addition, they postulated that P, Ca, K, Mg, and Fe in field-grown quinoa are present in concentrations suitable for a balanced human diet. However, mineral concentration data for quinoa vary dramatically from one geographical region to another (Ballon *et al.*, 1984; Becker and Hanners, 1990; Cardoza and Tapia, 1979; Koziol, 1992; Varriano-Marston and de Francisco, 1984; Oshodi *et al.*, 1999). This variation may be due to the mineral composition of the soils in the various regions. In a controlled environment, the mineral composition can easily be manipulated for either optimal plant growth or for human consumption. In either case, quinoa seeds and leaves offer excellent sources of minerals.

Mineral nutrition is an important consideration in developing new crops for controlled-environment agriculture. Table 10 compares mineral tissue analyses of hydroponically and field-grown quinoa seed and leaf tissue. Most minerals are substantially more abundant in the hydroponically grown crop. A major concern with vegetarian diets is a deficiency in the alkali earth metals, most notably calcium and sodium. The NRC recommends that a human ingest 3.2 g NaCl per day. Most vegetarian diets are deficient in sodium and cannot fulfill this requirement. While most plant materials are low in sodium and calcium relative to animal products (Hoff *et al.*,

1982), quinoa is very high in both of these minerals and may prove to be an important source, especially for vegetarian diets.

Table 9. Comparative mineral nutrition values of quinoa seeds and some major grains.

Mineral	Concentration (mg/100 g)			
	Quinoa ¹	Wheat ²	Corn ²	White Rice ²
Calcium	160.0	46.0	3.0	24.0
Phosphorus	270.0	354.0	111.0	94.0
Iron	18.6	3.4	0.7	0.8
Sodium	3.6	3.0	trace	5.0
Potassium	2170.0	370.0	280.0	92.0

¹ Hydroponically grown.

² From Souci *et al.* (1994).

Table 11 compares hydroponically grown quinoa with similar field-grown leafy plants. All minerals, except sodium, were found in substantially higher concentrations than in spinach and cabbage, which are considered to be good crops for supplying minerals to a human diet. Sodium was found in lower concentrations (leaf and stem tissue) due to the low levels added into the hydroponic nutrient solution.

Members of the Chenopodiaceae are known to accumulate large amounts of alkali ions, especially in their leaves. Some of the chenopodiaceous plants effectively transport sodium to their leaves, due to a preference for sodium in xylem transport (Reimann and Breckle, 1993), whereas others reabsorb sodium from the xylem sap and retain it in the basal parts of the plant (Johanson and Cheeseman, 1983). The high

Table 10. Tissue mineral analysis of all plant parts of *C. quinoa* grown in hydroponic solution and under field conditions.

Treatment	P	Mg	K	Ca	S	Na	Zn	Cu	Fe	Mn
	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Hydroponic										
Roots	0.85	0.84	3.89	1.67	–	1232.0	80.10	13.62	2076.0	1592.0
Stems	0.18	0.11	3.26	0.99	–	48.55	26.61	0.23	88.57	27.23
Leaves	0.37	0.94	11.81	2.92	0.69	158.9	88.29	3.52	293.1	353.1
Seeds	0.27	0.92	2.17	0.16	0.24	35.75	94.20	1.62	185.9	47.47
Field										
Seeds ¹	0.33	0.28	0.80	0.08	–	96.00	25.30	0.08	7.98	2.79
Leaves ²	0.04	0.08	0.38	0.15	–	2890	5.90	0.70	8.70	–

¹ From Souci *et al.* (1994).² From Koziol (1992).

alkali ion concentrations are found not only in the halophytic species but in the mesophytes as well (Albert, 1982; Reimann and Breckle, 1993). In this study, calcium concentrations in the hydroponically grown quinoa leaves were significantly higher (2.92%) than in the field (0.15%) (Table 10), which may be explained by the relatively high solution concentrations of calcium. Sodium concentrations in the leaf tissue of hydroponically grown quinoa were significantly lower (159 ppm) than the reported field values for quinoa leaves (2890 ppm) (Table 10). Because of the potential for uptake of the elements, it may be possible to add significant amounts of these elements to the hydroponic solution in order to satisfy human nutritional requirements. Further studies into calcium and sodium relations of quinoa in controlled-environment, hydroponic systems need to be pursued.

In a related application, quinoa may also prove useful in the removal of sodium from waste streams. NASA is currently developing fully regenerative life-support systems for long-term space travel (Bubenheim, 1991). These systems will require

recovery and re-utilization of all waste products. Sodium is found in very high concentrations in urine and wash water (Wydeven *et al.*, 1983). If a plant could be used as a sink for sodium and other minerals, it might prove to be an inexpensive, low weight substitute for bulkier physical or chemical methods of mineral removal. In addition, because of the salt tolerance of this crop, quinoa could be cultivated on salt-laden soils or in areas where salt water intrusion has occurred. Growing it on infertile or depleted soils is another example of the versatility of this plant as a crop.

Table 11. Mineral nutrition values of hydroponically quinoa leaves compared with other major leafy vegetable crops grown in the field.

Nutrient	Nutrient Concentration (mg/100 g)		
	Quinoa Leaves ¹	Spinach Leaves ²	Cabbage Leaves ²
Calcium	2920.0	126.0	35.0
Phosphorus	370.0	55.0	30.0
Iron	29.3	4.1	0.5
Sodium	15.9	65.0	4.0
Potassium	1181.0	633.0	266.0

¹ Hydroponically grown.

² From Souci *et al.* (1994).

Anti-Nutritional Factors

The pericarp of the quinoa fruit contains saponins, ranging from 0.01 to 4.65 as a percent of dry weight (Koziol, 1992). Saponins are also found in the leaves of both bitter and sweet cultivars selected for reduced concentration of saponins in the fruit. Leaf saponin content increases with maturity but remains lower than the content found in the fruit (Mastebroek *et al.*, 2000). Saponins are in a structurally diverse group of naturally occurring glycosides found mainly in plants (Price *et al.*, 1987). They are found in significant concentrations in a number of commercially important crops, including bean, pea, peanut, onion, garlic, and asparagus. They impart a bitter taste and

tend to foam in aqueous solution. Separation of saponins from quinoa seed can be accomplished by rinsing the seed in cold alkaline water or by mechanical abrasion of the surface. Saponins are useful in producing soaps, detergent, shampoos, cosmetics, and pharmaceuticals (Johnson and Ward, 1993). Until recently, saponins have been considered to be highly toxic. While they appear to be toxic to cold-blooded animals, the oral toxicity to mammals is low. Saponins present in common foods, including quinoa, are free from significant oral toxicity in humans (Oser, 1966; Ishaaya *et al.*, 1969; Phillips *et al.*, 1979; Malinow *et al.*, 1982, 1984; Oakenfull and Sidhu, 1990).

Some literature indicates that saponins may even be beneficial in the human diet. Sidhu *et al.* (1987) revealed that soy saponins form insoluble complexes with cholesterol in the human blood stream and inhibit intestinal cholesterol absorption. Adding alfalfa saponins to high cholesterol diets fed to monkeys prevented hypercholesterolemia (Malinow *et al.*, 1977). The source of the protein has been found to be critical in the influence of the proteins, in conjunction with saponins, on lipid metabolism (Potter *et al.*, 1993; Samman *et al.*, 1989; Ho *et al.*, 1989; Gaddi *et al.*, 1991). Potter *et al.* (1993) examined the interactions between proteins and saponins and their impact on cholesterol metabolism. Quillaja (*Quillaja saponaria*) saponins and casein formed a high molecular weight complex that significantly decreased the LDL cholesterol and LDL/HDL ratios in gerbils. In the same study, the addition of quillaja saponin to isolated soy protein resulted in no change to the serum lipid concentrations. Thus the source of the saponin and its effect on serum lipids were dependent on the source of the dietary protein (Potter *et al.*, 1993). The chemical structure of saponins varies widely, with the number of variations in the hundreds. Effects from saponins on cholesterol metabolism are dependent on the chemical structure (Malinow, 1984). While saponins have been isolated and examined from quinoa (Mizui *et al.*, 1988; Ridout *et al.*, 1991), no detailed examination of quinoa

saponins and their cholesterolemic effects has been made. However, there is still conflicting information on the PER and biological value (BV) associated with saponins. For example, Ruales and Nair (1992) reported that quinoa saponins do not exert any negative effect on the nutritive quality of the protein, while Chauhan *et al.* (1999) reported that extraction of the saponins increased PER and did not affect the BV.

Phytic acid is another important so-called "anti-nutritional" factor found in many cereal grains, legumes, and oilseeds, including quinoa fruits. In the gastrointestinal tract, it can form insoluble complexes with divalent cations such as Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} , and Zn^{2+} (Zhou and Erdman, 1995). These insoluble complexes decrease the bioavailability of the nutrients to humans. However, phytic acid is known to be a natural anti-oxidant (Graf *et al.*, 1984) and thus may exert anticarcinogenic benefits (Thompson and Zhang, 1991). *In vitro* studies demonstrated that phytic acid reduced cell proliferation rates in erythroleukemia (Shamsuddin *et al.*, 1992) and in human mammary cancer (Shamsuddin *et al.*, 1996). Furthermore, the levels of phytic acid in quinoa (0.54 g/100 g) are lower than in most grains (Souci *et al.*, 1994).

CONCLUSIONS

Quinoa responded well to controlled-environment practices with large increases in seed production, maintenance of short canopy stature, and increased harvest index, as compared to growth in the field. The very desirable nutritional composition, which led us to our original interest in quinoa, was enhanced in controlled environments. The protein values increased, and the relative proportions of amino acids, except cyst(e)ine and methionine, met or exceeded the requirements of humans. The mineral concentration was exceptional and has the potential of being easily manipulated in hydroponic culture to meet the dietary needs for human nutrition.

As population increases and expands into prime agriculture regions, we not only need to grow more food but higher quality food on poorer and poorer substrates. New and more efficient methods of crop production need to be investigated. In addition, the most efficient, productive, and nutritional crops should be examined. There are very few examples where nutrition directed the planning of agricultural research, and there is little evidence of agronomic research being specifically planned to resolve particular nutritional problems (Tripp, 1990). As we progress through the new millennium, approaches to agricultural design based on nutritional needs, similar to the approaches in this paper and others (Bubenheim, 1997; Bubenheim *et al.*, 1995b; Cenci-McGrody and Quay-Stiller, 1997), must be considered as a method for producing high productivity crops that provide outstanding nutritional quality and can be sustained on poor substrates or hydroponically in a restricted area.

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