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Greg Schlick
and David L. Bubenheim

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Quinoa: An Emerging "New" Crop with Potential for CELSS

Greg Schlick
and David L. Bubenheim
Ames Research Center, Moffett Field, California

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Ames Research Center
Moffett Field, California 94035-1000

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NOMENCLATURE

M	molar
mM	millimolar
$Ca(NO_3)_2 \cdot 4H_2O$	calcium nitrate, tetrahydrate
$CuSO_4 \cdot 5H_2O$	copper (II) sulfate, pentahydrate
$FeCl_3$ + HEDTA	iron (III) chloride, hexahydrate + N – (2-hydroxyethyl) ethylenediamine triacetic acid
$FeNO_3 \cdot 9H_2O$	iron (III) nitrate, septihydrate
H_3BO_3	boric acid
HNO_3	nitric acid
K_2SO_4	potassium sulfate
KH_2PO_4	potassium dihydrogen phosphate
KNO_3	potassium nitrate
$MgSO_4 \cdot 7H_2O$	magnesium sulfate, heptahydrate
$MnCl_2 \cdot 4H_2O$	manganese dichloride, tetrahydrate
$Na_2Mo_4 \cdot 2H_2O$	disodium molybdate, dihydrate
$ZnSO_4 \cdot 7H_2O$	zinc sulfate, heptahydrate

QUINOA: AN EMERGING "NEW" CROP WITH POTENTIAL FOR CELSS

Greg Schlick and David L. Bubenheim

Ames Research Center

SUMMARY

Chenopodium quinoa is being considered as a new crop for the Controlled Ecological Life Support System (CELSS) because of its high protein values (12–18%) and unique amino acid composition. Lysine, an essential amino acid that is deficient in many grain crops, is found in quinoa approaching Food and Agriculture Organization of the United Nations (FAO) standards set for humans. This "new" crop, rich in protein and with desirable proportions of important amino acids, may provide greater versatility in meeting the needs of humans on long-term space missions. Initially, the cultivars CO407 × ISLUGA, CO407 Heat Tolerant Population 1, and Real' (a Bolivian variety) were examined. The first cultivar showed the most promise in greenhouse studies. When grown hydroponically in the greenhouse, with no attempt to maximize productivity, this cultivar produced 202 g m^{-2} with a harvest index of 37%. None of the cultivars were greater than 70 cm in height. Initial results indicate that quinoa could be an excellent crop for CELSS because of the high concentration of protein, ease of use, versatility in preparation, and potential for greatly increased yields in controlled environments.

INTRODUCTION

It is likely that NASA will embark on a long-term human space mission, and that mission will require the crew to have a nutritionally balanced diet. The CELSS program has been evaluating growth and productivity of several crops in a controlled-environment culture, with the goal of selecting those meeting nutritional needs and exhibiting a manageable growth habit. Quinoa (*Chenopodium quinoa* Willd.) is being considered as a new crop for CELSS because of its high protein value (12–18%) and unique amino acid composition. Quinoa, (pronounced keen-wa) a relatively new crop for the United States, has been overlooked, until recently, by most commercial and experimental farmers outside of South America. Of primary interest is the high lysine value, which is unusual in the plant kingdom. Quinoa is also high in the essential sulfur-containing amino acids—methionine and cyst(e)ine. These and other essential amino acids approach or exceed the values set by the FAO. Currently, CELSS has found it necessary to combine nutritional value of crops (i.e., soybeans (*Glycine max*) and wheat (*Triticum aestivum*)) to obtain a suitable amino acid pattern to meet nutritional needs of humans. Quinoas' amino acid pattern is very similar to the combination of soybeans and wheat, and may provide a suitable alternative. While no single food can supply all the essential life sustaining nutrients, quinoa comes as close as any other in the plant or animal kingdom (White et al., 1955).

Initial testing in the greenhouse indicated that quinoa responded well to hydroponic culture in controlled environment production; growth was rapid and seed production good. Given these encouraging observations, a series of greenhouse production studies and seed germination trials were initiated.

General Characteristics of Quinoa

Quinoa is a member of the Goosefoot Family (Chenopodiaceae), which includes such plants as sugar beets, Swiss chard (*Beta sp.*), spinach (*Spinacia oleracea*), and Lamb's quarters (*Chenopodium album*). The latter has been a nuisance weed to farmers in many regions of the United States. Quinoa is an annual herb that produces a panicle containing small seeds called achenes. The seeds are small (200–500 seeds g^{-1}), round, flat and approximately 2–3 mm in diameter. The seeds are found in a large array of pigments, from white and yellow to red, purple, and black, which are probably associated with "eco-type" and vary from region to region. The root system is extensive. It consists of many branches from a central tap root which may extend 30 cm in a field environment. Quinoa plants range in height from 60 to 125 cm, depending on the eco-type. The upper leaves are lanceolate while the lower leaves are more rhomboidal. The upper and lower surfaces of the leaves are covered with small glands. Quinoa is found in severe environments such as the "altiplano" (high mountain plains) and alkaline salt flats, to relatively moderate, fertile valley areas and moist coastal forests. Quinoa is a diet staple in the high regions of the Andes because corn and wheat cannot compete at these high altitudes and, in some cases, cannot even grow in the harsh conditions of these areas.

Past and Present Agronomic Uses of Quinoa

Quinoa is thought to have originated in the altiplano region of Peru and Bolivia in the South American Andes. The altiplano is the region of high mountain plains (most of which exceed 3,600 m elevation) of southern Peru, western Bolivia, and northern Chile and Argentina. Quinoa was the staple of the Inca Empire for many centuries. In many areas of South America, but especially in the Andes, quinoa seeds are utilized to make flour for biscuits and cakes, added directly into soups, eaten as a breakfast-type cereal and even used to make a very popular fermented drink (*chicha blanca*). 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.

Yields were typically low under traditional farming conditions (450–900 kg ha^{-1}) for several reasons: the traditional harvest and processing techniques are time consuming and, in the areas of cultivation, there is a need to produce only what you can use. Today, with improved commercial and experimental farming harvesting and processing techniques, yields greater than 2,200–3,300 kg ha^{-1} are becoming common (Cusack, 1984). Quinoa is currently being cultivated in Bolivia, Chile, Ecuador, Peru and recently in the United States by Colorado State University (CSU).

Nutritional Quality and Uses of Quinoa

Quinoa has an excellent balance between oil, fat, and protein and has a unique composition of amino acids (table 1). One of the key essential amino acids, lysine, which is relatively uncommon within the plant kingdom, comes very close to the standards set by the FAO for human nutritional needs.

Table 2 compares several major grains with quinoa. Quinoa compares favorably with all the grains and has a good balance between protein and carbohydrates. The pericarp of the seed contains as much as 6% saponins. The saponins are plant glycosides which are probably utilized by the plant as a predator deterrent. These compounds, which are bitter tasting, must be removed prior to consumption. Saponins may interfere with digestion by directly interacting with the digestive enzymes, preventing absorption of nutrients. Removal of the saponins can be accomplished by rinsing the quinoa in cold water or mechanically rubbing the outer layer from the seed. An improved variety called "sajama" has been develolped in Bolivia; it is free of saponins and can be processed directly for food (FAO, 1989). There are a great number of color varieties found in quinoa. The colors are probably due to habitat (eco-type) differences. Table 3 illustrates the nutritional variation among the varieties of quinoa. Additional benefits of quinoa are the mild, pleasant taste and ease of preparation. It is usually cooked like rice and has a very mild taste with a texture similar to cooked barley. In addition, quinoa can be eaten like a hot

Table 1. Essential amino acid profile (g/16g nitrogen) of field-grown quinoa compared with wheat, soybean and the FAO standard amino acid profile for human nutrition[a]

Amino acid	Quinoa	Wheat	Soybean	FAO
Isoleucine	4.0	3.8	4.7	4.0
Leucine	6.8	6.6	7.0	7.0
Lysine	5.1	2.5	6.3	5.5
Phenylalanine	4.6	4.5	4.6	-
Tyrosine	3.8	3.0	3.6	-
Phenylalanine plus Tyrosine	8.4	7.5	8.2	6.0
Cyst(e)ine	2.4	2.2	1.4	-
Methionine	2.2	1.7	1.4	-
Cystine plus Methionine	4.6	3.9	2.8	3.5
Threonine	3.7	2.9	3.9	4.0
Tryptophan	1.2	1.3	1.2	1.0
Valine	4.8	4.7	4.9	5.0

[a]Johnson and Aguilera, 1980.

Table 2. Nutritional analysis of field-grown quinoa compared with various grains[a]

Crop	% Water	% Crude protein	% Fat	% Carbohydrate	% Fiber	% Ash
Barley	9.0	14.7	1.1	67.8	2.0	5.5
Buckwheat	10.7	18.5	4.9	43.5	18.2	4.2
Corn	13.5	8.7	3.9	70.9	1.7	1.2
Millet	11.0	11.9	4.0	68.6	2.0	2.0
Oats	13.5	11.1	4.6	57.6	10.3	2.9
Quinoa	12.6	13.8	5.0	59.7	4.1	3.4
Rice	11.0	7.3	0.4	80.4	0.4	0.5
Rye	13.5	11.5	1.2	69.6	2.6	1.5
Wheat	10.9	13.0	1.6	70.0	2.7	1.8

[a]Johnson and Croissant, 1985.

Table 3. Nutritional analysis of several varieties of quinoa[a]

Composition	(% dry mass)		
	Red	Yellow	White
Carbohydrate	68.4	68.5	74.3
Protein	15.35	15.95	14.05
Fat	7.5	6.15	7.15
Ash	3.05	3.65	2.4
Saponin	3.7	3.9	3.4

[a]DeBruin, 1964.

breakfast cereal, as a side dish in a dinner meal, or put in soups, salads, pilafs, and desserts. With the increasing availability of quinoa, many unique cooking methods are being developed, multiplying the ways this food can be prepared. With all these benefits, quinoa may allow greater versatility in meeting the nutritional needs of humans on long-term space missions.

Agronomic Cultivation and Research

Research in the cultivation of quinoa is now in full swing in many South American countries. For the past 15 years, universities in the United States have been exploring quinoa as a "new" food crop. Early experimental plantings of quinoa in Pennsylvania and Minnesota failed. However, CSU has had some success, and is continuing its research. CSU is growing quinoa at high elevations in Colorado (2,100–3,000 m). The high elevation was chosen because at temperatures above 35°C the vegetative plant becomes dormant or suffers pollen sterility (Johnson, 1988). Plant spacing is approximately 35 cm, resulting in a stand of 53,000 plants ha^{-1}.

Variety/Cultivar Selection for CELSS Research

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 grows at an altitude of 2,100–4,000 meters, is 2.5 meters in height, and matures in 5–7 months. Altiplano quinoa grows at altitudes greater than 3,600 meters, is 1.0–1.8 meters in height, and matures in 4–5 months. Salt flat quinoa grows in salt-deposit areas between 3,000–3,600 meters elevation, and grows taller and matures slower than the altiplano group. Sea level quinoa grows at low altitudes, is 1.0–1.8 meters in height, and matures slower than the altiplano group.

For CELSS research purposes, the altiplano group was chosen because of its shorter growth habits and its relatively quick maturation times.

PRELIMINARY RESEARCH WITH QUINOA FOR CELSS

Materials and Methods

Greenhouse trials– At Ames Research Center, two cultivars were received from Duane Johnson at CSU (CO407 × ISLUGA and CO407 Heat Tolerant Population 1) and one variety from Bolivia (Real'). Initial results showed that quinoa responded well to hydroponic culture; growth was rapid and seed production was good.

These cultivars of *Chenopodium quinoa* were planted at a density of 256 plants m^{-2}, whereas production field density is normally 30–50 plants m^{-2}. Seeds were manually placed in precut, prerinsed rockwool. The rockwool flats were placed on hydroponic trays in a greenhouse. Greenhouse temperature was maintained at 22°C. The nutrient solution (table 4) was maintained at a pH of 5.8 and a electrical conductivity of 0.9 milliSiemans. Adjustments to the pH were made automatically by a controller and metering pump supplying 0.5M HNO_3. Nutrient solution level was automatically controlled by a float valve and centrifugal pump. Conductivity was recorded and modified manually each day.

Germination studies– Germination studies were performed to better analyze germination and growth in the greenhouse study. The cultivars CO407 × ISLUGA and CO407 Heat Tolerant Population 1, and the variety Real' were included in the study. For germination, 15 cm glass petri dishes were used. Each petri dish had four sheets of Whatman 42 filter paper and 40 ml of distilled water. Twenty uniformly sized seeds were placed on the premoistened filter paper. The seeds were monitored for germination rate and vigor. Germination rate was calculated by using a weighted germination percentage,

$$\frac{(8xn_1 + 7xn_2 + \ldots + 1xn_8) \times 100}{N \times 8}$$

where $n1$–$n8$ are the number of seeds germinated from the first through the eighth day, the numbers 8, 7,...,1 are the weights given on each of those days, and N is the number of the seeds in the trial (Reddy, Metzger, and Ching, 1985). Growth values were recorded daily and rated as follows: 0 = no germination; 1 = radicle emergence; 2 = radicle longer than the seed.

Results

Greenhouse trials– After 30 days the plants were approximately 40 cm in height. Rapid uptake of nutrients began and lasted for the next 25 days and a noticeable increase in canopy density occurred during this phase. The Real' cultivar showed a similar nutrient uptake, but not the dramatic growth that was noted in the other cultivars. Flowering occurred 24, 27, and 30 days after planting for the CO407 × ISLUGA, CO407 Heat Tolerant Population 1, and Real', respectively (table 5). Average heights at harvest were 68, 59, and 62 cm, for CO407 × ISLUGA, CO407 Heat Tolerant Population 1, and Real'. Seeding to harvest required 89 days for Real' and 103 days for both CSU cultivars. Total biomass production was high for the CSU cultivars and relatively low for Real'(table 6). The shoot/root ratio was 16.80, 12.00, 10.90 for the CO407 × ISLUGA, CO407 Heat Tolerant Population 1, and Real', respectively. The CSU cultivar CO407 × ISLUGA showed the best production in all categories: seed yield, harvest index, 100 seed weight, and seeds per plant (table 7). The seed yield was more than twice the amount seen in CO407 Heat Tolerant Population 1 and more than five times that of Real'. Harvest index showed a similar result and was two times greater than the other cultivars. The high yield in CO407 × ISLUGA resulted from high individual seed weight (shown as 100 seed weight) and the quantity of seeds per plant compared to the other cultivars.

Table 4. Nutrient solution for *Chenopodium quinoa* in greenhouse trials

Nutrient	Molecular weight	Solution concentration
$Ca(NO_3)_2 \cdot 4H_20$	236.15	2 mM
KNO_3	101.11	2 mM
KH_2PO_4	136.09	0.6 mM
$MgSO_4 \cdot 7H_2O$	246.47	0.5 mM
K_2SO_4	174.27	0.5 mM
$FeNO_3 \cdot 9H_2O$	404.01	10 uM
$FeCl_3$ + HEDTA	548.58	45 uM
$MnCl_2 \cdot 4H_2O$	197.92	3 uM
$ZnS0_4 \cdot 7H_2O$	287.56	3 uM
$CuSO_4 \cdot 5H_2O$	249.68	0.18 uM
$Na_2Mo_4 \cdot 2H_2O$	241.96	0.09 uM
H_3BO_3	61.84	2 uM

Table 5. Harvest plant height, days to flower, and days to harvest for three quinoa cultivars

Cultivar	Height (cm)	Days to flower	Days to harvest
CO407 × ISLUGA	68	24	103
CO407 Heat Tolerant Population 1	59	27	103
Real'	62	30	89

Table 6. Biomass production and distribution of three quinoa cultivars

Cultivar	Total biomass ($g\ m^{-2}$)	Shoot mass ($g\ m^{-2}$)	Root mass ($g\ m^{-2}$)	Shoot/root ratio
CO407 × ISLUGA	542.00	511.80	30.50	16.80
CO407 Heat Tolerant Population 1	453.10	418.20	34.80	12.00
Real'	183.50	168.10	15.40	10.90

Table 7. Seed yield, harvest index, and yield components of three quinoa cultivars

Cultivar	Seed yield ($g\ m^{-2}$)	Harvest index (%)	Mean no. of seeds per plant	Seed mass ($g\ seed^{-1}$)
CO407 × ISLUGA	202.0	0.37	699	0.34
CO407 Heat Tolerant Population 1	81.0	0.17	249	0.28
Real'	37.40	0.28	502	0.28

Germination studies– Seed obtained from CSU germinated similarly, with approximately 95–98% germination, and a high calculated vigor rate. The Real' cultivar germinated poorly (45–50% germination), but the seeds that did germinate exhibited a high calculated vigor rate. Quinoa seed harvested from the greenhouse experiments showed a high calculated germination percentage (95–98%) and exhibited a high calculated vigor rate.

CONCLUSIONS

Quinoa responds well to controlled-environment production practices. The altiplano quinoa varieties, according to Tapia (1979), should mature in 4–5 months. In our controlled-environment experiments, maturation time has been decreased to 3 months. This decrease in maturation time will increase the annual yield due to an increase in successive plantings.

The cultivar CO407 × ISLUGA performed much better in controlled-environment production than the other selections. Seed yield and harvest index of the cultivar CO407 × ISLUGA was much higher than the other selections and it has great potential for crop improvement with cultivated breeding programs. All cultivars exhibited a manageable size and growth habit in a controlled-environment culture. CO407 Heat Tolerant Population 1 and Real' showed low seed yield and harvest index. Real' also demonstrated a very low seed germination rate and seedling vigor. The problem with Real' was probably due to old seed stock. Real' seeds collected from these studies have demonstrated germination rate and seedling vigor similar to that of the other cultivars. The cultivars CO407 × ISLUGA and Real' will continue to be included in CELSS research. The cultivar CO407 Heat Tolerant Population 1 will not be considered further. While it is reported to withstand stress and maintain a reasonable level of productivity, it did not respond positively to the non-stress growing conditions of a controlled environment.

Quinoa has desirable food qualities for CELSS application—high protein and desirable amino acid composition. In addition, the ease with which it can be prepared and combined with other crops makes quinoa an ideal candidate crop for CELSS.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California
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Chenopodium quinoa is being considered as a new crop for the Controlled Ecological Life Support System (CELSS) because of its high protein values (12–18%) and unique amino acid composition. Lysine, an essential amino acid that is deficient in many grain crops, is found in quinoa approaching Food and Agriculture Organization of the United Nations (FAO) standards set for humans. This "new" crop, rich in protein and with desirable proportions of important amino acids, may provide greater versatility in meeting the needs of humans on long-term space missions. Initially, the cultivars CO407 × ISLUGA, CO407 Heat Tolerant Population 1, and Real' (a Bolivian variety) were examined. The first cultivar showed the most promise in greenhouse studies. When grown hydroponically in the greenhouse, with no attempt to maximize productivity, this cultivar produced 202 g m^{-2} with a harvest index of 37%. None of the cultivars were greater than 70 cm in height. Initial results indicate that quinoa could be an excellent crop for CELSS because of the high concentration of protein, ease of use, versatility in preparation, and potential for greatly increased yields in controlled environments.

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