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Chenopodium quinoa—An Indian perspective

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Abstract

Chenopodium quinoa Willd. is a pseudocereal that has been cultivated in the Andean region for thousands of years. It is an annual broad-leaved plant, 1–2 m tall with deep penetrating roots and can be cultivated from sea level upto an altitude of 3800 m. The plant shows tolerance to frost, salinity and drought, and has the ability to grow on marginal soils. Quinoa grain is highly nutritious due to its outstanding protein quality and wide range of minerals and vitamins. The grain protein is rich in amino acids like lysine and methionine that are deficient in cereals. The grain is used to make flour, soup, breakfast, cereal and alcohol, while the flour is utilized in making biscuits, bread and processed food. Quinoa starch having small grains and high viscosity, can be exploited for various industrial applications. The crop is self-pollinated with low outcrossing rates. Emasculation and hybridization are cumbersome due to small size of the flowers, but male sterility in some cultivars and gynomonoecious breeding system may help breeding research in this crop. Quinoa's ability to produce high-protein grains under ecologically extreme conditions makes it important for the diversification of future agricultural systems, especially in high-altitude area of the Himalayas and North Indian Plains.

Keywords: *Chenopodium quinoa*; Saponins; Protein; Breeding; Male sterility; Stress conditions

1. Introduction

The genus *Chenopodium* (family Chenopodiaceae) comprises about 250 species (Giusti, 1970), which include herbaceous, suffrutescent and arborescent perennials, although most species are colonizing annuals (Wilson, 1990). *Chenopodium* spp. have been cultivated for centuries as a leafy vegetable (*Chenopodium album*) as well as an important subsidiary grain crop (*Chenopodium quinoa* and *C. album*) for human and animal foodstuff due to high-protein and a balanced amino-acid spectrum with high lysine (5.1–6.4%) and methionine (0.4–1.0%) contents (Prakash and Pal, 1998; Bhargava et al., 2003a). *C. quinoa* Willd. is a native of the Andean region and is a member of the subsection Cellulata of the section *Chenopodium* of the genus *Chenopodium*. It belongs to the group of crops known as pseudocereals (Cusack, 1984; Koziol, 1993) that includes other domesticated chenopods, amaranths and buckwheat. The grain has a high-protein content with abundance of essential amino acids, and a wide

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range of vitamins and minerals (Repo-Carrasco et al., 2003). Recently, there has been growing interest in a number of countries (especially in Europe), initiating introduction and research work on quinoa (Galwey, 1992; Jacobsen, 2003). The aim of the paper is to review the existing literature and explore the potential of this crop for agricultural as well as various industrial purposes, especially for India and other countries having similar agro-climatic conditions.

2. History

Quinoa has been an important food grain source in the Andean region since 3000 B.C. (Tapia, 1982) and occupied a place of prominence in the Inca empire only next only to maize (Cusack, 1984). However, after the conquest of the region by the Spaniards in 1532 A.D., other crops, such as potato and barley, relegated quinoa to the background. However, the sporadic failure of green revolution in the Andes and enormous destruction of other crops by droughts, once again brought native crops, like quinoa, to the forefront as it showed much less fall in the yields in severe conditions (Cusack, 1984).

3. Distribution

Quinoa is grown in a wide range of environments in the South American region (especially in and around the Andes), at latitudes from 20° N in Columbia to 40° S in Chile, and from sea level to an altitude of 3800 m (Risi and Galwey, 1989a). The distribution starts from Narino to the Salares of southern Bolivia that includes countries like Ecuador, Peru and northern Argentina (Jujuy and Salta provinces) (Wilson, 1990). The Atacama Desert forms a break in the distribution of the crop, which continues further south into Chile.

Recently, it has been introduced in Europe, North America, Asia and Africa. Many European countries are members in the project entitled 'Quinoa—A multipurpose crop for EC's agricultural diversification' which was approved in 1993. The American and European Test of quinoa have yielded good results and demonstrate the potential of quinoa as a grain and fodder crop (Mujica et al., 2001a; Casini, 2002; Jacobsen, 2003).

4. Cytotaxonomy

The domesticated species of *Chenopodium* are divided into two subsections on the basis of pericarp and perianth morphology, and crossing relationships (Wilson, 1990). The first subsection Cellulata contains diploid allotetraploids ($2n = 4x = 36$) like *C. quinoa* and *Chenopodium berlandieri* subsp. *nuttaliae*. The second subsection Leiosperma includes domesticated and semi-domesticated forms like *Chenopodium pallidicaule* ($2n = 18$) and *C. album* ($2n = 18, 36, 54$) (Wilson, 1980; Gangopadhyay et al., 2002). Detailed karyotypic studies have been performed in many wild and cultivated taxa of *Chenopodium* spp. (Bhargava et al., in press a). The symmetry index (TF%) in quinoa varies from 43.9 to 47.4%, and only a single satellite pair has been observed in all quinoa accessions studied, which has been corroborated by fluorescent in situ hybridization studies (Kolano et al., 2001). Our studies also show close karyotypic similarity between *C. quinoa* and *C. berlandieri* subsp. *nuttalliae* which is clear from the karyotypic formulae, symmetry index and one satellite pair of similar morphology (Bhargava et al., in press a).

5. Botanical description

Quinoa is a gynomonoecious annual plant with an erect stem, and bears alternate leaves that are variously coloured due to the presence of betacyanins. The plant shows good growth in India with many cultivars reaching upto 1.5 m in height, generally with large number of branches and a big leaf size (Bhargava et al., unpublished results). A well-developed, highly ramified tap-root system is present (Gandarillas, 1979), penetrating as deep as 1.5 m below the surface, which protects against drought conditions. The leaves exhibit polymorphism; the upper leaves being lanceolate while the lower leaves are rhomboidal (Hunziker, 1943).

The inflorescence is a panicle, 15–70 cm in length and rising from the top of the plant and in the axils of lower leaves. It has a principal axis from which secondary axis arise and is of two types, amaranthiform and glomerulate. An important feature of quinoa is the presence of hermaphrodite and unisexual female flowers (Hunziker,

1943; Simmonds, 1965). The hermaphrodite ones are located at the distal end and bear five perianth lobes, five anthers and a superior ovary with two or three stigmatic branches (Hunziker, 1943). Some cultivars show male sterility in some or all female flowers.

The fruit is an achene, comprising several layers, viz. perigonium, pericarp and episperm (Risi and Galwey, 1984), from outwards to inside, and may be conical, cylindrical or ellipsoidal, with saponins concentrated in the pericarp. Seed size and colour are variable (Mujica, 1994) where black is dominant over red and yellow, which in turn are dominant to white seed colour (Risi and Galwey, 1984).

6. Effect of temperature and photoperiod on quinoa

Bertero et al. (1999b) showed that photoperiodic sensitivity was negatively associated with the latitude of origin of nine quinoa lines and positively associated with minimal time taken from emergence to visible flower buds, when temperature and photoperiod responses were taken as independent (non-interactive). However, photoperiod and temperature parameters when taken as independent (interactive) were not significantly related with latitudes of origin. Furthermore, short-day treatment showed a quantitatively positive response for time to anthesis and total number of leaves while maximum seed growth was obtained under short day and cool temperature treatment (Bertero et al., 1999a). Another study (Bertero et al., 2000) has shown that photoperiod sensitivity of phyllochron decreased as the latitude of origin of the cultivar increased. Temperature sensitivity was highest in cultivars originating in cold or dry climates, and lowest for cultivars from humid and warmer climates. Bertero's (2001) study has indicated that mean incident radiation affects the phyllochron in quinoa. Radiation sensitivity was reported to be highest in cultivars from Peru, Bolivia and Southern Chile, and lowest in those from Ecuador, which had high sensitivity to photoperiod and longest phyllochron. Experiments conducted under controlled environments have demonstrated that quinoa cultivars studied had a facultative short-day response for duration of emergence to flowering (Bertero, 2003) and the duration of all the phases of development is sensitive to photoperiod.

7. Crop production and management

Quinoa can be grown on various types of soils, including marginal soils with a wide pH range (Jacobsen and Stolen, 1993; Tapia, 1979). Although, sowing can be done in rows, groups, mixed, broadcast or by transplanting, row spacing of 25–50 cm is preferable since it allows easy hoeing. A level, well-drained seedbed is most suited for quinoa cultivation. Seeds should be sown 1–2 cm deep in a fine structured, moist seed bed (Jacobsen, 2003).

Quinoa responds well to nitrogenous fertilizers, but high levels of available nitrogen are reported to decrease yield due to slow maturity and intense lodging (Oelke et al., 1992). However, recent studies (Berti et al., 2000; Schulte-auf'm-Erley et al., 2005) suggest that quinoa responds strongly to nitrogen fertilization, and grain yield did not show decrease with increasing N rates. Nitrogen application is known to increase seed yield as well as the protein content of the seeds (Johnson and Ward, 1993). Heavy doses of phosphorus and potash are known to increase vegetative growth without any increase in seed yield (Etchevers and Avila, 1979). But, this could be due to excess of soil potassium in the tropical Andean soils. However, Gandaillas (1982) stated that quinoa showed no response for either potassium or phosphorus.

Quinoa is a drought-tolerant crop having low water requirement, though yield is significantly affected by irrigation (Oelke et al., 1992). Excessive irrigation in the seedling stage causes diseases like stunting and damping off, while such conditions after stand establishment produce tall plants with no yield improvement (Oelke et al., 1992). Maximum yields of 1439 kg/ha on sandy loam soils were obtained with 208 mm of water (rainfall and irrigation) (Flynn, 1990), but it cannot be called conclusive since the study was limited to a single location and soil type. The low water requirement shows its drought-hardy nature and makes it suitable for cultivation on large tracts of India where assured irrigation is non-existent and farmers have to depend on seasonal rains.

Weed control has major impact on grain yield. Utmost care should be taken in regulation of sowing dates in quinoa because of slow growth during the first two weeks after emergence, during which competition from rapidly growing weeds is greater. An early sowing would enable quinoa to have a head start over weeds

as the plant can attain good growth during this period. This is more important, since there is an absence of any recommendation or use of herbicides to control weed populations in quinoa and generally hand weeding is done. Pigweed, kochia, lambsquarters and sunflower are the common weeds in North America, while our experience has shown that *Parthenium*, *C. album* and *Sysmbrium* are the commonest weeds in the North-Indian Plains.

The drying of the plant and shedding of leaves signifies the mature stage of the plant. Seeds can be threshed by traditional methods like sticks or animals, as well as by threshers (Risi and Galwey, 1984). A fanning mill and gravity separator is necessary to remove trash from the seed after combining (Oelke et al., 1992). Grains should be totally dry before storage.

8. Diseases and pests

Quinoa is infected by a variety of pathogens, which cause several diseases like mildews, damping off, blight, mosaic, etc. (Table 1). Viruses are known to infect the plant, but reports of significant damage are absent. Downy mildew is the most severe pathogen on quinoa and is known to cause yield reduction of 33–58%, even in the most resistant cultivars (Danielsen et al., 2000). Danielsen and Munk (2004) tested seven disease-assessment methods to measure downy mildew severity on quinoa and found the three-leaf model as the best to predict yield loss. However, our studies (Kumar et al., unpublished results) showed that the two-point assessment method (Jeger and Viljanen-Rollinson, 2001) was most suited for predicting yield loss in Indian conditions. Quinoa showed high level of resistance towards downy mildew in North-Indian conditions. The peak severity stage across all accessions coincided with the flower-bud initiation stage, and thereafter, gradually decreased (Kumar et al., unpublished results).

Insect pests attacking quinoa and causing damage ranging from 8 to 40% (Ortiz and Zanabria, 1979) are given in Table 2. Birds also attack quinoa, primarily in the inflorescence stage. But these cause minor damage, as quinoa is conferred with a chemical defence in the form of saponins that confer resistance against pests and birds (Risi and Galwey, 1984).

Table 1
Some common diseases of quinoa and their causal organism

S. no.	Disease	Type	Causal organism	References
1.	Damping off	Fungi	*Sclerotium rolfsii*	Danielsen et al. (2003)
2.	Stalk rot	Fungi	*Phoma exigua* var. *foveata*	Alandia et al. (1979); Danielsen et al. (2003)
3.	Downy mildew	Fungi	*Peronospora farinosa*	Danielsen et al. (2001); Danielsen and Munk (2004)
4.	Stem gothic spot	Fungi	*Phoma cava*	Alandia et al. (1979)
5.	Gray mould	Fungi	*Botrytis cinerea*	Johanson (1983)
6.	Leaf spot	Fungi	*Ascochyta hyalospora*	Danielsen et al. (2003)
7.	Bacterial blight	Bacteria	*Pseudomonas* sp.	Alandia et al. (1979)
8.	Chlorotic mosaic	Virus	Chenopodium mosaic virus	Alandia et al. (1979); Tomlinson et al. (1981)
9.	False nodule	Nematode	*Nacobbus* spp., *Thecavermiculatus* spp.	Alandia et al. (1979); Franco (2003)

Table 2
Insects and pests, their infective stages causing diseases on various plant parts of quinoa

Type	Causal organism	Stage	Plant part affected	References
Leaf miner	*Lyriomiza brasiliensis*	Larva	Leaf	Ortiz and Zanabria (1979)
Leaf sticker, Kcona kcona	*Eurysacca* spp.	Larva	Inflorescence, stored grain	Galwey (1989); Rasmussen et al. (2003)
Cutworm	*Feltia experta, Spodoptera* spp.	Caterpillar	Stem, leaf	Zanabria and Mujica (1977); Rasmussen et al. (2003)
Looper	*Perisoma sordescens*	Caterpillar	Leaf, seed, inflorescence	Zanabria and Mujica (1977)
Leaf and inflorescence caterpillar	*Hymenia recurvalis, Pachyzancla bipunctales*	Caterpillar	Leaf, inflorescence	Ortiz and Zanabria (1979)
Defoliating insects	*Epithrix subcrinita, Epicauta* spp.	Adult	Leaf, inflorescence	Zanabria and Mujica (1977); Ortiz and Zanabria (1979)
Piercing and cutting insects	*Macrosiphum* spp., *Myzus persicae, Bergallia* spp., *Franklinella tuberosi*	Adult	Whole plant	Ortiz and Zanabria (1979)

9. Economic uses

Quinoa is highly nutritive and is being used to make flour, soup, breakfast and alcohol. It is sold either as whole grain that is cooked as rice or in combination dishes. It can be fermented to make beer, or used to feed livestock (Galwey, 1989). Whole plant is also used as green fodder to feed cattle, pigs and poultry. In Peru and Bolivia, quinoa flakes, tortillas, pancakes and puffed grains are produced commercially (Popenoe et al., 1989). The use of quinoa for medicinal purposes has been rarely reported (Mujica, 1994). The plant is reportedly used in inflammation, as analgesic and as a disinfectant of the urinary tract. It is also used in fractures and internal hemorrhaging and as an insect repellant (Mujica, 1994). These reports can open new avenues for its use as a medicinal crop.

The starch of *C. quinoa* is highly suitable for emulsion food products (Ahamed et al., 1996a). Quinoa is being considered as a potential crop for NASA's Controlled Ecological Life Support System (CELSS), which aims to utilize plants to remove carbon dioxide from the atmosphere and generate food, oxygen and water for the crew of long-term space missions (Schlick and Bubenheim, 1996).

Quinoa flour, in combination with wheat flour or corn meal, is used in making biscuits, bread and processed food. The seed flour has good gelation property, water-absorption capacity, emulsion capacity and stability (Oshodi et al., 1999). Quantitative analysis of quinoa flour and its comparison with other cereals has shown that quinoa flour yielded free sugars like glucose (4.55%), fructose (2.41%) and sucrose (2.39%) (Gonzalez et al., 1989). Ogungbenle (2003) evaluated the sugar content and chemical composition of seed flour of quinoa and stated that it has high proportion of D-xylose (120 mg/100 g), and maltose (101 mg/100 g), and a low content of glucose (19 mg/100 g) and fructose (19.6 mg/100 g). Thus, quinoa could be effectively utilized in the beverage industry for the preparation of malted drink formulations. Another study showed increase in the level of insulin-like growth factor-1 (IGF-1) in the plasma of children who consumed a supplementary portion of an infant food prepared by drum drying a pre-cooked slurry of quinoa flour (Ruales et al., 2002). The highly nutritious quinoa flour could be used to supplement protein deficient wheat flour, commonly used for human consumption in India.

10. Chemistry: quality aspects

10.1. Leaves

Quinoa leaves contain ample amount of ash (3.3%), fibre (1.9%), nitrates (0.4%), vitamin E (2.9 mg α-TE/100 g) and Na (289 mg/100 g) (Koziol, 1992). Prakash et al. (1993) reported that leaves have about 82–190 mg/kg of carotenoids, 1.2–2.3 gm/kg of vitamin C and 27–30 gm/kg of proteins. Study on fresh leaves (Bhargava et al., unpublished results) revealed abundant moisture (83.92–89.11%), chlorophyll a (0.48–1.82 mg/g), chlorophyll b (0.25–0.07 mg/g) and much higher amount of leaf carotenoid (230.23–669.57 mg/kg) than that reported earlier.

10.2. Grain

Quinoa is referred as pseudo-oilseed crop (Cusack, 1984) due to exceptional balance between oil, protein and fats. Perisperm, embryo and endosperm are the three areas where reserve food is stored in quinoa seed (Prego et al., 1998). Starch is stored in the perisperm, and lipids and protein in the endosperm and embryo. The nutritional value of quinoa grain has long been known to be superior to cereals and milk solids in feeding trails (White et al., 1955). Results have indicated that upto 150 g/kg unprocessed or dehulled quinoa seed could be included in broiler feed (Jacobsen et al., 1997). The incorporation of quinoa in poultry feeds can greatly benefit poultry industry.

Starch content varies from 51 to 61%, and consists of uniform small granules less than 3 μm in diameter (Atwell et al., 1983). Koziol (1992) also gave similar value for starch content (52–60% of grain weight) and found varying size of starch granules (0.7 and 3.2 μm). Quinoa starch has the potential that can be used for specialized industrial applications due to its small granules and high viscosity (Galwey et al., 1990). Starches having small-sized granules could serve as dusting starches in cosmetics and rubber tyre mould release agents. Quinoa starch displays A-type crystalline packing arrangement and annular polygonal granules (Wright et al., 2002a). The starch gelatinizes at about 56–58 °C (Swinkels, 1985) and shows a single-stage swelling in the temperature range of 65–95 °C, which along with its opaque nature makes it highly suitable for emulsion food products. Quinoa starch also has non-edible potential for utilization as biodegradable fillers in low-density polyethylene (LDPE) films (Ahamed et al., 1996b). This aspect needs more probes for its effective utilization in the food, pharmaceutical and textile industry. Because of better mechanical properties, quinoa starch can be utilized in the manufacture of carrier bags where tensile strength is important. Studies on freeze-thaw stability of quinoa starch have shown that its paste is resistant to retrogradation suggesting applications in frozen- and emulsion-type food products (Ahamed et al., 1996a).

Grains have an average of about 4.1% fibre with a range from 1.1 to 16.32% (Cardozo and Tapia, 1979). De Bruin (1964) reported 3.4% fibre content that is much higher than that of rice (0.4%), wheat (2.7%) and corn (1.7%).

The ash content of quinoa (3.4%) (Cardozo and Tapia, 1979), is higher than that of rice (0.5%), wheat (1.8%) and other traditional cereals. Quinoa grains contain large amounts of minerals like Ca, Fe, Zn, Cu and Mn (Repo-Carrasco et al., 2003). Calcium and iron are significantly higher than most commonly used cereals (Table 3). Ruales and Nair (1992) also reported large amounts of iron (81 mg/kg) and calcium (874 mg/kg) in quinoa. It has about 0.26% of magnesium in comparison to 0.16% of wheat and 0.14% of corn.

Several studies have revealed that the oil content in quinoa ranges from 1.8 to 9.5%, with an average of 5.0–7.2% (Table 4) that is higher than that of maize (3–4%) (Mounts and Anderson, 1983). Quinoa oil is rich in essential fatty acids, like linoleate and linolenate (Koziol, 1990) and has a high concentration of

Table 3
Mineral content of quinoa grain (ppm) as compared to other cereals (Johnson and Ward, 1993)

Crop	Calcium	Phosphorus	Iron	Potassium	Sodium	Zinc
Quinoa	1274	3869	20	6967	115	48
Barley	880	4200	50	5600	200	15
Beans	1191	3674	86	10982	103	32
Wheat	550	4700	50	8700	115	14

Table 4
Fat content in quinoa grain (%)

References	Range	Mean
De Bruin (1964)	5.5–6.7	6.2
Cardozo and Tapia (1979)	1.8–9.3	5.0
Koziol (1990)	4.3–9.5	7.2

natural antioxidants like α-tocopherol (5.3 mg/100 g) and γ-tocopherol (2.6 mg/100 g) (Ruales and Nair, 1992). Repo-Carrasco et al. (2003) have reported the concentrations of α- and γ-tocopherol as 721.4 and 797.2 ppm, respectively. The antioxidant activity of quinoa might be of particular interest to the medical researchers and needs more attention towards its utilization as a potent antioxidant. Given the high quality of its oil, and the fact that some varieties show fat concentrations upto 9.5%, quinoa has been considered as a potentially valuable new oil crop (Koziol, 1993).

There are few reports on vitamin content of quinoa grain. Ruales and Nair (1992) have reported appreciable amounts of thiamin (0.4 mg/100 g), folic acid (78.1 mg/100 g) and vitamin C (16.4 mg/100 g). Koziol (1992) gave riboflavin and carotene content as 0.39 mg/100 g and 0.39 mg/100 g respectively. In terms of 100 g edible portion, quinoa supplies 0.20 mg vitamin B_6, 0.61 mg pantothenic acid, 23.5 μg folic acid and 7.1 μg biotin (Koziol, 1992). Repo-Carrasco et al. (2003) have also reported that quinoa is rich in vitamin A, B_2 and E.

The protein content in grain ranges from 7.47 to 22.08% with an average 13.81% (Cardozo and Tapia, 1979). Wright et al. (2002b) reported 14.8 and 15.7% of protein for sweet and bitter quinoa, respectively. Albumin and globulins are the major protein fraction (44–77% of total protein) while the percentage of prolamines is low (0.5–0.7%) (Koziol, 1992). The protein quality of quinoa grain is superior to most cereal grains including wheat (Table 5). The seeds have a balanced amino acid spectrum with high lysine, histidine and methionine (Van Etten et al., 1963; Koziol, 1992). The content of essential amino acids in quinoa is higher than in common cereals (Ruales and Nair, 1992; Wright et al., 2002b). The high protein quality and energy value of the grain can be utilized in poultry industry. Quinoa is considered as one of the best leaf-protein concentrate source (Carlsson et al., 1985) and so has the potential as protein substitute for food and pharmacuetical industry.

11. Saponins

Saponins are the principle antinutritional factors present in the seed coat of quinoa. The saponin content in seeds of sweet genotypes varies from 0.2 to 0.4 g/kg dry matter and in bitter genotypes from 4.7 to 11.3 g/kg dry matter (Mastebroek et al., 2000). Saponins in quinoa are basically glycosidic triterpenoids with glucose constituting about 80% of the weight. Saponin content is affected by soil-water deficit, high water deficit lowering the saponin content (Soliz-Guerrero et al., 2002). Saponin content also differs in different growing stages, low saponin is found in the branching stage and high in the blooming stage. They are removed either by the wet method, i.e. washing and rubbing in cold water, or by dry method, i.e. toasting and subsequent rubbing of the grains to remove the outer layers (Risi and Galwey, 1984). On commercial scale, saponins are removed by abrasive dehulling (Reichert et al., 1986), but in this method, some saponin remains attached to the perisperm (Becker and Hanners, 1991). Saponin removal by dry method reduces the vitamin and mineral content to some extent,

Table 5
Comparative picture of the amino acid composition of some common cereals and quinoa (percent amino acids in total protein)

Amino acid	Quinoa Van Etten et al. (1963)	Wheat Janssen et al. (1979)	Soybean Janssen et al. (1979)	Barley Janssen et al. (1979)
Lysine	6.6	2.9	6.4	3.6
Isoleucine	6.4	3.8	4.9	3.8
Threonine	4.8	3.1	4.2	3.5
Methionine	2.4	1.7	1.4	1.7
Histidine	2.7	2.2	2.5	2.2
Cystine	2.4	2.3	1.5	2.3
Glycine	5.2	4.0	4.2	4.0

the loss being significant in case of potassium, iron and manganese (Ruales and Nair, 1992).

Saponins have immense industrial importance and are used in the preparation of soaps, detergents, shampoos, beer, fire extinguishers and photography, cosmetic and pharmaceutical industries (Johnson and Ward, 1993). They have the ability to induce changes in intestinal permeability (Johnson et al., 1986; Gee et al., 1989), which aids in the absorption of particular drugs (Basu and Rastogi, 1967). Saponins are also known to lower blood cholesterol levels (Oakenfull and Sidhu, 1990). Research has proved that quinoa saponins may have the potential to serve as adjuvants for mucosally administered vaccines (Estrada et al., 1998). Seeing the pharmaceutical potential of saponins, efforts should be made towards the utilization of quinoa saponins for this purpose.

12. Breeding approaches

The basic objective of breeding in quinoa is the development of a variety with high grain yield accompanied with high protein and low saponin content. However, it is not so easy due to self-pollinated nature of the crop. The problem is compounded, since the flowers are very small, as a result of which emasculation and hybridization is very tedious and difficult. Inspite of these difficulties, mass selection and hybridization has been practiced in quinoa (Risi and Galwey, 1984). Various techniques of emasculation in quinoa have been suggested but these are cumbersome procedures. An easy approach can be the utilization of morphological markers to distinguish the hybrid from the parents. Seeing the emerging potential of the crop and a very limited research work on breeding aspects, there is an urgent need to initiate elaborate breeding programmes in quinoa (conventional as well as biotechnological) for its genetic improvement.

The plant is mainly self-pollinated, but out crossing rates upto 17.36% have been reported in quinoa (Silvestri and Gil, 2000). Out crossing occurs frequently upto a distance of 1 m and occasionally upto 20 m (Gandarillas, 1979). Risi and Galwey (1989b) assessed genetic diversity in 294 accessions of quinoa using principal component and canonical analysis. Accessions from near sea level in Chile formed a homogenous group. Ortiz et al. (1999) created a phenotypic distance matrix among 76 accessions from a Peruvian quinoa core collection. Rojas et al. (2003) analyzed the genetic diversity in *C. quinoa* using three multivariate methods. Multiple group discriminant function analysis resulted in six statistically significant functions, which separated the different groups. Genetic divergence for various morphological and quality traits was assessed in *C. quinoa* and *C. berlandieri* subsp. *nuttalliae* (Bhargava et al., unpublished results) in Indian conditions. The first principal component accounted for 39.5% of the total variation and had inflorescence/plant, plant height and stem diameter as the traits with highest coefficients. Seed protein had negative values for the first three components, but contributed to the fourth component with highest positive value. Although, reports on morphological diversity are abundant, but such information on diversity in seed protein profiles in quinoa are rare. A comparison of seed protein profiles of 40 cultivated and wild taxa of *Chenopodium* (Bhargava et al., in press b) showed genetic similarity of *C. quinoa* with *C. berlandieri* subsp. *nuttalliae* (26.5–64.5%) and *C. bushianum* (39.3–76.2%). Eight taxa of *C. quinoa* showed 43.8–73.9% similarity amongst themselves that are in accordance with the results obtained from allozyme diversity (Wilson, 1988a,b) and DNA analysis (Ruas et al., 1999).

A study of the genotype × environment interaction (GEI) by Risi and Galwey (1991) demonstrated that GEI differed among the variables measured. Grain yield was strongly dependent on the variety, but micronutrient deficiency and weed competition affected the varieties differently. Jacobsen et al. (1996) studied the stability of quantitative traits in 14 lines of *C. quinoa* and suggested that selection for height, inflorescence size and developmental stage could be easily performed at an early stage of breeding programme. Studies on developmental stability have suggested selection of early, uniformly maturing plant with more branches, low saponin content and high seed yield (Jacobsen, 1998) for North European conditions. The size and nature of the GEI for grain yield and grain size have been examined in a multi-environment trial at 14 sites across three continents (Bertero et al., 2004). The GEI to genotypic component of variance ratio was 4:1 and 1:1 for grain yield and grain size, respectively.

A high level of grain saponin is a major impediment in the diversification of this crop. Ward (2000) screened

10 South-American quinoa accessions for saponin content and performed three cycles of pedigree selection. The results indicated that dominant gene action is a major component of genetic variance for the trait. Fixed heterozygosity at loci controlling saponin content may also occur due to allotetraploid nature of the crop.

Keeping in view the tremendous scope of this crop, National Botanical Research Institute, Lucknow, has initiated an extensive breeding programme, which is a coordinated effort of various departments like Plant Breeding and Genetics, Plant Pathology, Lipid Chemistry, Experimental Taxonomy, Biomass Biology, etc. The main objective is genetic improvement in *C. quinoa* and development of high-yielding varieties suited to Indian conditions. Morphological variability and various selection parameters were assessed in 44 germplasm lines of *Chenopodium* spp. (Bhargava et al., unpublished results). Phenotypic coefficient of variation (PCV) and Genotypic coefficient of variation (GCV) values were maximum for leaf size, followed by dry weight/plant and 100 seed weight. Heritability and genetic gain was high for most of the characters. The genetic interrelationship between grain yield and its 10 contributing traits was worked out in *Chenopodium* spp. (Bhargava et al., 2003b). Traits like inflorescence length, inflorescence/plant, dry weight/plant and leaf size had significant positive association with grain yield and high positive direct path. These traits were found to be important components to build an ideal plant type for increased grain yield. Bhargava et al. (2004) assessed the suitability of making direct and indirect selection for grain yield in grain chenopods through different contributing traits. Inflorescence length exhibited maximum selection efficiency, followed by dry weight/plant and plant height.

13. Male sterility

Clustering of numerous small-sized flowers on the inflorescence makes hybridization by manual emasculation extremely difficult. Therefore, the development of male sterile quinoa lines to be used as maternal parent in hybrid production has been proposed by many researchers as an alternative (Wilson, 1980; Risi and Galwey, 1984; Fleming and Galwey, 1995). Several efforts have been made in this direction. Simmonds (1971) extensively studied the genetics of male sterility and reported three loci: R (red plant) r (green plant); Ax (axil spot) ax (none), and Ms (hermaphrodite) ms (male sterile). The plants of genotype MsMs and Msms were fertile, and the recessive msms breeds were male sterile as they carried an erratically expressed or transmitted cytoplasmic factor for male sterility. Ward and Johnson (1993) isolated a cultivar ‘Apelawa’ carrying normal and male sterile cytoplasms. The plants having male sterile cytoplasm produced flowers characterized by complete absence of anthers and prominent exertion of stigmas. The cross between male sterile and normal male fertile donors consistently produced male sterile offspring, while interspecific crosses between male sterile quinoa plants and related wild species *C. berlandieri* produced offsprings with partial restoration of male fertility. Inspite of obtaining male sterile cytoplasm, a reliable restorer system could not be found. Further, Ward and Johnson (1994) reported that plants of Bolivian quinoa (*C. quinoa* Willd.) cv. ‘Amachuma’ carried a single nuclear recessive gene that in homozygous state produces normal anthers devoid of pollen grains. The plants heterozygous at this locus are indistinguishable from homozygous male fertile ones, and further segregation for male sterility follows a normal Mendelian single-gene segregation pattern. However, they suggested that this form of male sterility is of limited use in hybrid quinoa production due to poor stigma exsertion resulting in inefficient pollination. Ward (1998) found an accession PI 510536 in the USDA-ARS collection, which had normal hermaphrodite and male sterile quinoa plants. This male sterility was of cytoplasmic nature and was characterized by small shrunken anthers and absence of pollen. It was interesting that a dominant nuclear allele that interacted with this male sterile cytoplasm to restore male fertility was present in this accession. The ratio between male fertile and male sterile plants, observed in F_1 and F_2 generations of the crosses between male sterile, and the plants carrying restorer allele suggested either duplication of the restorer locus within the quinoa genome or tetraploid segregation. These characters may definitely facilitate hybrid production in quinoa. Still, there is a need to obtain restorer lines, which can facilitate the easy production of hybrids and may overcome the extreme difficulty in hybridization process.

14. Tolerance in relation to stress conditions

Quinoa exhibits high level of resistance to several predominant adverse factors, like soil salinity, drought, frost, diseases and pests (Jacobsen et al., 2003). It can tolerate soil pH from 4.8 to 9.5 because of mycorrhizal associations, thus maximizing the use of scarce nutrients (Tapia, 1979; Mujica, 1994) and also resists frost before the flower-bud formation stage (Jacobsen et al., 2005). Moreover, it accumulates salt ions in tissues, which adjusts leaf water potential, enabling the plant to maintain cell turgor and limit transpiration under saline conditions (Jacobsen et al., 2001). In addition, significant increase in leaf area at salinity level of 11 dSm^{-1} as compared to 3 dSm^{-1} control has been noted (Wilson et al., 2002). Bhargava et al. (2003c) obtained marginal decrease in grain yield of quinoa on sodic soil (pH 8.5–9.0) in comparison to normal soil, and stem diameter, inflorescence/plant and dry weight/plant were determined as factors controlling grain yield on sodic soil.

The drought resistance of quinoa is attributed to morphological characters, such as an extensively ramified root system and presence of vesicles containing calcium oxalate that are hygroscopic in nature and reduce transpiration (Canahua, 1977). Physiological characters indicating drought resistance is low osmotic potential, low turgid weight/dry weight ratio, low elasticity and an ability to maintain positive turgor even at low leaf water potentials (Andersen et al., 1996). Vacher (1998) analyzed the responses of quinoa to drought and found that stomatal conductance remained relatively stable with low but ongoing gas exchange under very dry conditions and low leaf-water potentials. Quinoa maintained high leaf-water use efficiency to compensate for the decrease in stomatal conductance. and thus, optimized carbon gain with a minimization of water losses. Jensen et al. (2000)

Table 6
Performance of some quinoa accessions at N.B.R.I., Lucknow, India (2002–2003 and 2003–2004)

Germplasm line	Source	Origin[a]	Altitude[a] (m)	Seed yield (kg/ha)
C. quinoa Willd. CHEN 58/77	IPK, Germany	–	4000	2108
C. quinoa Willd. CHEN 67/78	IPK, Germany	Puno, Peru	–	3750
C. quinoa Willd. CHEN 71/78	IPK, Germany	Bolivia	–	3266
C. quinoa Willd. CHEN 33/84	IPK, Germany	–	–	1333
C. quinoa Willd. CHEN 84/79	IPK, Germany	Cuzco, Peru	3200	3441
C. quinoa Willd. CHEN 92/91	IPK, Germany	Columbia	–	2250
C. quinoa Willd. CHEN 7/81	IPK, Germany	–	–	9833
C. quinoa Willd. PI 614938	USDA	Oruro, Bolivia	–	316
C. quinoa Willd. PI 478408	USDA	La Paz, Bolivia	3800	466
C. quinoa Willd. PI 478414	USDA	La Paz, Bolivia	3800	6083
C. quinoa Willd. PI 596498	USDA	Cuzco, Peru	3030	3933
C. quinoa Willd. Ames 13219	USDA	La Paz, Bolivia	3700	2800
C. quinoa Willd. Ames 13719	USDA	New Mexico, USA	–	9333
C. quinoa Willd. PI 587173	USDA	Jujuy, Argentina	–	3175
C. quinoa Willd. PI 510532	USDA	Peru	3000	1683
C. quinoa Willd. PI 614883	USDA	Jujuy, Argentina	–	1000
C. quinoa Willd. PI 584524	USDA	Chile	–	6600
C. quinoa Willd. Ames 22156	USDA	Chile	–	5033
C. quinoa Willd. Ames 13762	USDA	New Mexico, USA	–	8500
C. quinoa Willd. PI 614881	USDA	Jujuy, Argentina	–	8250
C. quinoa Willd. PI 510537	USDA	Peru	–	4391
C. quinoa Willd. PI 510547	USDA	Peru	–	4700
C. quinoa Willd. Ames 22158	USDA	Chile	–	4850
C. quinoa Willd. PI 510536	USDA	Peru	–	675
C. quinoa Willd. PI 478410	USDA	La Paz, Bolivia	3800	3133
C. quinoa Willd. PI 433232	USDA	Chile	–	3575
C. quinoa Willd. Ames 21909	USDA	Oruro, Bolivia	3870	9083

[a] From germplasm database.

studied the effects of soil drying on leaf-water relations and gas exchange in *C. quinoa*. High net photosynthesis and specific leaf-area (SLA) values during early vegetative growth probably resulted in early vigor of the plant supporting early water uptake, and thus, tolerance to a following drought. The leaf water relations were characterized by low osmotic potentials and low turgid weight/dry weight (TW/DW) ratios during later growth stages sustaining a potential gradient for water uptake and turgor maintenance under high evaporation demands. Garcia et al. (2003) calculated the seasonal yield response factor (K_y) for quinoa that was lower to that of groundnut and cotton. This low K_y value for quinoa indicated that a minor drought stress does not result in large yield decrease.

15. Quinoa in Indian perspective

India, located between 8° and 38°N and 68° and 93.5°E, exhibits enormous diversity for agro-climatic regions and edapho-climatic conditions. An increasing population in this region of the world demands not only an increase in food grain production but also a shift towards environmentally sound sustainable agriculture. Quinoa can play a major role in future diversification of agricultural systems in India, not only in the Himalayan region, but also in the North-Indian Plains. Trials at N.B.R.I. (120 m above sea level) have shown that the crop can be successfully cultivated in this region, with many cultivars giving high grain yield (Bhargava et al., unpublished results) (Table 6). Quinoa can be termed 'underutilized', especially for India, since inspite of its wide adaptability, rusticity and nutritional superiority, its commercial potential has remained untapped. In India, a large portion of the population has little access to protein-rich diet, since rice and wheat are the principal food crops. Quinoa's highly proteinaceous grain can help to make diets more balanced in this region and can play an important role in combating 'silent hunger' among poor populations in India who have little access to protein-rich diet. Besides this, improved technologies and link with other areas, like product development and marketing, would enable the industry to tap its potential for diverse applications.

16. Concluding remarks

Quinoa's ability to produce high protein grains under ecologically extreme conditions makes it important for the diversification of future agricultural systems, especially in high-altitude area of the Himalayas and North-Indian Plains. The high nutritional quality and multiple uses in food products make quinoa ideal for utilization by the food industry. Other potential uses reviewed by the industry include use of quinoa as a flow improver in starch flour products, fillers in plastic industry, anti-offset and dusting powders and complementary protein for improving the amino acid balance of human and animal foods. Efforts should be made to evolve edible varieties with high-quality components, low saponin content, better yield and large seed size. Making quinoa popular in India would require dissemination of information about the crop among the farmers as well as the consumers, proper marketing and efficient post-harvest technologies. Quinoa has the potential to shed its underutilized status and become an important industrial and food crop of the 21st century.

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References

Ahamed, N.T., Singhal, R.S., Kulkarni, P.R., Pal, M., 1996a. Physicochemical and functional properties of *Chenopodium quinoa* starch. Carbohydr. Polym. 31, 99–103.

Ahamed, N.T., Singhal, R.S., Kulkarni, P.R., Kale, D.D., Pal, M., 1996b. Studies on *Chenopodium quinoa* and *Amaranthus paniculatas* starch as biodegradable fillers in LDPE films. Carbohydr. Polym. 31, 157–160.

Alandia, S., Otazu, V., Salas, B., 1979. Quinua y Kaniwa. Cultivos Andinos. In: Tapia, M.E. (Ed.), Serie Libros y Materiales Educativos, vol. 49. Institoto Interamericano de ciencias Agricolas, Bogota, Columbia, pp. 137–148.

Andersen, S.D., Rasmussen, L., Jensen, C.R., Mogensen, V.O., Andersen, M.N., Jacobsen, S.E., 1996. Leaf water relations and gas exchange of field grown *Chenopodium quinoa* Willd. dur-

ing drought. In: Stolen, O., Pithan, K., Hill, J. (Eds.), Small Grain Cereals and Pseudocereals. Workshop at KVL, Copenhagen, Denmark.

Atwell, W.A., Patrick, B.M., Johnson, L.A., Glass, R.W., 1983. Characterization of quinoa starch. Cereal Chem. 60, 9–11.

Bertero, H.D., de la Vega, A.J., Correa, G., Jacobsen, S.E., Mujica, A., 2004. Genotype and genotype-by-environment interaction effects for grain yield and grain size of quinoa (*Chenopodium quinoa* Willd.) as revealed by pattern analysis of international multi-environment trials. Field Crops Res. 89 (2–3), 299–318.

Basu, N., Rastogi, R.P., 1967. Triterpenoid saponins and sapogenins. Phytochemistry 6, 1249–1270.

Becker, R., Hanners, G.D., 1991. Composition and nutritional evaluation of quinoa whole grain flour and mill fractions. Lebensmittel-Wissenschaft Technologie 23, 441–444.

Bertero, H.D., 2001. Effects of photoperiod, temperature and radiation on the rate of leaf appearance in quinoa (*Chenopodium quinoa* Willd.) under field conditions. Ann. Bot. 87 (4), 495–502.

Bertero, H.D., 2003. Response of developmental processes to temperature and photoperiod in quinoa (*Chenopodium quinoa* Willd.). Food Rev. Int. 19 (1–2), 87–97.

Bertero, H.D., King, R.W., Hall, A.J., 1999a. Photoperiod-sensitive development phases in quinoa (*Chenopodium quinoa* Willd.). Field Crops Res. 60, 231–243.

Bertero, H.D., King, R.W., Hall, A.J., 1999b. Modelling photoperiod and temperature responses of flowering in quinoa (*Chenopodium quinoa* Willd.). Field Crops Res. 63, 19–34.

Bertero, H.D., King, R.W., Hall, A.J., 2000. Photoperiod and temperature effects on the rate of leaf appearance in quinoa (*Chenopodium quinoa*). Aus. J. Plant Physiol. 27 (4), 349–356.

Berti, M., Wilckens, R., Hevia, F., Serri, H., Vidal, I., Mendez, C., 2000. Fertilizacion nitrogenada en quinoa (*Chenopodium quinoa* Willd.). Ciencia e Investigacion Agraria 27 (2), 81–90.

Bhargava, A., Shukla, S., Ohri, D., 2003a. Genetic variability and heritability of selected traits during different cuttings of vegetable *Chenopodium*. Ind. J. Genet. Plant Breed. 63 (4), 359–360.

Bhargava, A., Shukla, S., Ohri, D., 2003b. Genetic association in *Chenopodium*. Ind. J. Genet. Plant Breed. 66 (3), 283–284.

Bhargava, A., Shukla, S., Katiyar, R.S., Ohri, D., 2003c. Selection parameters for genetic improvement in *Chenopodium* grain on sodic soil. J. Appl. Hort. 5 (1), 45–48.

Bhargava, A., Shukla, S., Ohri, D., 2004. Correlated response of various economic traits in Chenopodium spp. J. Med. Arom. Pl. Sci. 26, 493–497.

Bhargava, A., Shukla, S., Ohri, D., in press-a. Karyotypic studies on some cultivated and wild species of *Chenopodium* (Chenopodiaceae). Gen. Res. Crop. Evol.

Bhargava, A., Rana, T.S., Shukla, S., Ohri, D., in press-b. Seed protein electrophoresis of some cultivated and wild species of *Chenopodium* (Chenopodiaceae). Biologia Plantarum.

Canahua, M.A., 1977. Observaciones del comportamiento de quinoa a la sequia. In: Primer Congreso Internacional sobre cultivos Andinos, Universidad Nacional San Cristobal de Huamanga, Instituto Interamericano de Ciencias Agricolas, Ayacucho, Peru, pp. 390–392.

Cardozo, A., Tapia, M.E., 1979. Valor nutritivo. Quinua y Kaniwa. Cultivos Andinos. In: Tapia, M.E. (Ed.), Serie libros y Materiales educativos, vol. 49. Instituto Interamericano de Ciencias Agricolas, Bogota, Columbia, pp. 149–192.

Carlsson, R., Hanczakowski, P., Partap, T., Mathew, K.S., Atul, K.V.R., 1985. *Chenopodium album* in India, a food crop for the production of leaf protein concentrates. In: Proceedings of the International Conference of Leaf Protein Research, August 22–24, Nagoya University, Togocho, Japan.

Casini, P., 2002. Possibilita di introdurre la quinoa negli ambienti mediterranei. Informatore Agrario 27, 29–32.

Cusack, D., 1984. Quinoa: grain of the Incas. Ecologist 14, 21–31.

Danielsen, S., Munk, L., 2004. Evaluation of disease assessment methods in quinoa for their ability to predict yield loss caused by downy mildew. Crop Prot. 23, 219–228.

Danielsen, S., Jacobsen, S.E., Echegaray, J., Ames, T., 2000. Correlacion entre metodos de evaluacion y perdida de rendimiento en el patosistema quinua-mildiu. Fitopatologia 35 (4), 242–248.

Danielsen, S., Jacobsen, S.E., Echegaray, J., Ames, T., 2001. Impact of downy mildew on the yield of quinoa. In: CIP program report 1999–2000. International Potato Center, Lima, Peru, pp. 397–401.

Danielsen, S., Bonifacio, A., Ames, T., 2003. Diseases of quinoa (*Chenopodium quinoa*). Food Rev. Int. 19 (1–2), 43–59.

De Bruin, A., 1964. Investigation of the food value of quinoa and canihua seed. J. Food Sci. 29, 872–876.

Estrada, A., Li, B., Laarveld, B., 1998. Adjuvant action of *Chenopodium quinoa* saponins on the induction of antibody responses to intragastric and intranasal administered antigens in mice. Comp. Immunol. Microbiol. Infect. Diseases 21 (3), 225–236.

Etchevers, B.J., Avila, T.P., 1979. Factores que afectan el crecimiento de quinua (Chenopodium quinoa) en al centro-sur de Chile. Pap. 10th Lat. Am. Meet. Agric. Sci.

Fleming, J.E., Galwey, N.W., 1995. Quinoa (*Chenopodium quinoa*). In: Williams, J.T. (Ed.), Cereals and Pseudocereals. Chapman and Hall, London.

Flynn, R.O., 1990. Growth characteristics of quinoa and yield response to increase soil water deficit. M.S. Thesis. Colorado State Univ. Fort, Collins.

Franco, J., 2003. Parasitic nematodes of quinoa in the Andean region of Bolivia. Food Rev. Int. 19 (1–2), 77–85.

Galwey, N.W., 1989. Exploited plants—Quinoa. Biologist 36 (5), 267–274.

Galwey, N.W., 1992. The potential of quinoa as a multipurpose crop for agricultural diversification: a review. Ind. Crops Prod. 1 (2–4), 101–106.

Galwey, N.W., Leakey, C.L.A., Price, K.R., Fenwick, G.R., 1990. Chemical composition and nutritional characteristics of quinoa (*Chenopodium quinoa* Willd.). Food Sci. Nutr. 42F, 245–261.

Gandarillas, H., 1979. Botanica. Quinua y Kaniwa. Cultivos Andinos. In: Tapia, M.E. (Ed.), Serie Libros y Materiales Educativos, vol. 49. Instituto Interamericano de Ciencias Agricolas, Bogota, Columbia, pp. 20–44.

Gandaillas, H., 1982. Quinoa production. IBTA-CIID (Trans. by Sierra-Blanca Association, Denver, CO, 1985).

Gangopadhyay, G., Das, S., Mukherjee, K.K., 2002. Speciation in *Chenopodium* in West Bengal, India. Genet. Res. Crop Evol. 49, 503–510.

Garcia, M., Raes, D., Jacobsen, S.E., 2003. Evapotransporation analysis and irrigation requirements of quinoa (*Chenopodium quinoa*) in the Bolivian highlands. Agr. Water Manag. 60, 119–134.

Gee, J.M., Price, K.R., Ridout, I.T., Johnson, I.T., Fenwick, G.R., 1989. Effects of some purified saponins on transmural potential difference in mammalian small intestine. Toxicol. In Vitro 3, 85–90.

Giusti, L., 1970. El genero *Chenopodium* en Argentina 1: Numeros de cromosomas. Darwiniana 16, 98–105.

Gonzalez, J.A., Roldan, A., Gallardo, M., Escudero, T., Prado, F.E., 1989. Quantitative determinations of chemical compounds with nutritional value from Inca crops: *Chenopodium quinoa* ('quinoa'). Plant Foods Hum. Nutr. 39 (4), 331–337.

Hunziker, A.T., 1943. Los especies alimenticias de *Amaranthus* y *Chenopodium* cultivadas por los Indios de America. Rev. Argen. Agron. 30, 297–353.

Jacobsen, E.E., Skadhauge, B., Jacobsen, S.E., 1997. Effect of dietary inclusion of quinoa on broiler growth performance. Animal Feed Sci. Technol. 65, 5–14.

Jacobsen, S.E., 1998. Developmental stability of quinoa under European conditions. Ind. Crops Prod. 7, 169–174.

Jacobsen, S.E., 2003. The worldwide potential of quinoa (*Chenopodium quinoa* Willd.). Food Rev. Int. 19 (1–2), 167–177.

Jacobsen, S.E., Stolen, O., 1993. Quinoa—morphology, phenology and prospects for its production as a new crop in Europe. Euro. J. Agron. 2 (1), 19–29.

Jacobsen, S.E., Hill, J., Stolen, O., 1996. Stability of quantitative traits in quinoa (*Chenopodium quinoa* Willd). Theo. Appl. Gen. 93 (1–2), 110–116.

Jacobsen, S.E., Monteros, C., Christiansen, J.L., Bravo, L.A., Corcuera, L.J., Mujica, A., 2005. Plant responses of quinoa (*Chenopodium quinoa* Willd.) to frost at various phenological stages. Eur. J. Agro. 22 (2), 131–139.

Jacobsen, S.E., Mujica, A., Jensen, C.R., 2003. The resistance of quinoa (*Chenopodium quinoa* Willd.) to adverse abiotic factors. Food Rev. Int. 19 (1–2), 99–109.

Jacobsen, S.E., Quispe, H., Mujica, A., 2001. Quinoa: an alternative crop for saline soils in the Andes. In: Scientist and Farmer-Partners in Research for the 21st Century. CIP Program Report 1999–2000, pp. 403–408.

Janssen, W.M.M., Terpstra, K., Beeking, F.F.E., Bisalsky, A.J.N., 1979. Feeding Values for Poultry, second ed. Spelderholt Institute for Poultry Research, Beekbergen, Netherlands.

Jeger, M.J., Viljanen-Rollinson, S.L.H., 2001. The use of area under the disease progress curve (*AUDPC*) to assess quantitative disease resistance in crop cultivars. Theor. Appl. Genet. 102, 32–40.

Jensen, C.R., Jacobsen, S.E., Andersen, M.N., Nunez, N., Andersen, S.D., Rasmussen, L., Mogensen, V.O., 2000. Leaf gas exchange and water relation characteristics of field quinoa (*Chenopodium quinoa* Willd.) during soil drying. Eur. J. Agron. 13, 11–25.

Johanson, A., 1983. The resistance of quinoa (*Chenopodium quinoa*) to Downy Mildew (*Peronospora farinosa*), Brown Stalk Rot (*Phoma exigua* var. foveata) and Grey Mould (*Botrytis cinerea*). B.A. Research Project, Department of Applied Biology, University of Cambridge, Cambridge, England.

Johnson, D.L., Ward, S.M., 1993. In: Janick, J., Simon, J.E. (Eds.), Quinoa. New Crops. Wiley, New York, pp. 222–227.

Johnson, I.T., Gee, J.M., Price, K.R., Curl, C.L., Fenwick, G.R., 1986. Influence of saponins on gut permeability and active nutrient permeability in vitro. J. Nutr. 116, 2270–2277.

Kolano, B., Pando, L.G., Maluszynska, J., 2001. Molecular cytogenetic studies in *Chenopodium quinoa* and *Amaranthus caudatus*. Acta Societalis Botanicorum Poloniae 70, 85–90.

Koziol, M.J., 1990. Composicion quimica. In: Wahli, C. (Eds.), Quinua, hacia su cultivo commercial. Latinreco S.A., Casilla 17-110-6053, Quito, Equador, pp. 137–159.

Koziol, M.J., 1992. Chemical composition and nutritional value of quinoa (*Chenopodium quinoa* Willd.). J. Food Comp. Anal. 5, 35–68.

Koziol, M.J., 1993. In: Janick, J., Simon, J.E. (Eds.), Quinoa: A Potential New Oil Crop. New Crops. Wiley, New York, pp. 328–336.

Mastebroek, H.D., Limburg, H., Gilles, T., Marvin, H.J.P., 2000. Occurrence of sapogenins in leaves and seeds of quinoa (*Chenopodium quinoa* Willd.). J. Sci. Food Agr. 80 (1), 152–156.

Mounts, T.L., Anderson, R.A., 1983. Corn oil production, processing and use. In: Barnes, P.J. (Ed.), Lipids in Cereal Technology. Academic Press, New York, pp. 373–387.

Mujica, A., 1994. Andean grains and legumes. In: Hernando Bermujo, J.E., Leon, J. (Eds.), Neglected Crops: 1492 from a Different Perspective, vol. 26. FAO, Rome, Italy, pp. 131–148.

Mujica, A., Jacobsen, S.E., Ezquierdo, J., Marathee, J.P., 2001a. Resultados de la Prueba Americana y Europes de la Quinua. FAO, UNA-Puno, CIP, p. 51.

Oakenfull, D., Sidhu, G.S., 1990. Could saponins be a useful treatment for hypercolesterolaemia? Eur. J. Clin. Nutr. 44, 79–88.

Oelke, E.A., Putnam, D.H., Teynor, T.M., Oplinger, E.S., 1992. Alternative field crops manual. University of Wisconsin Cooperative Extension Service, University of Minnesota Extension Service, Centre for Alternative Plant and Animal Products.

Ogungbenle, H.N., 2003. Nutritional evaluation and functional properties of quinoa (*Chenopodium quinoa*) flour. Int. J. Food Sci. Nutr. 54 (2), 153–158.

Ortiz, R.V., Zanabria, E., 1979. Plagas. Quinua y Kaniwa. Cultivos Andinos. In: Tapia, M.E. (Ed.), Serie Libros y Materiales Educativos, vol. 49. Instituto Interamericano de Ciencias Agricolas, Bogota, Columbia, pp. 121–136.

Ortiz, R., Madsen, S., Ruiz-Tapia, E.N., Jacobsen, S.E., Mujica-Sanchez, A., Christiansen, J.L., Stolen, O., 1999. Validating a core collection of Peruvian quinoa germplasm. Gen. Res. Crop E 46 (3), 285–290.

Oshodi, A.A., Ogungbenle, H.N., Oladimeji, M.O., 1999. Chemical composition, nutritionally valuable minerals and functional properties of benniseed (*Sesamum radiatum*), pearl millet (*Pennisetum typhoides*) and quinoa (*Chenopodium quinoa*) flours. Int. J. Food Sci. Nutr. 50 (5), 325–331.

Popenoe, H., King, S.R., Leon, J., Kalinowski, L.S., 1989. Lost Crops of the Incas. In: Vietmeyer, N.D. (Ed.), Little Known Plants of the Andes with Promise for Worldwide Cultivation. National Academy Press, Washington.

Prakash, D., Pal, M., 1998. *Chenopodium*: seed protein, fractionation and amino acid composition. Int. J. Food Sci. Nutr. 49, 271–275.

Prakash, D., Nath, P., Pal, M., 1993. Composition, variation of nutritional content in leaves, seed protein, fat and fatty acid profile of *Chenopodium* species. J. Sci. Food. Agric. 62, 203–205.

Prego, I., Maldonado, S., Otegui, M., 1998. Seed structure and localization of reserves in *Chenopodium quinoa*. Ann. Bot. 82 (4), 481–488.

Rasmussen, C., Lagnaoui, A., Esbjerg, P., 2003. Advances in the knowledge of quinoa pests. Food Rev. Int. 19 (1–2), 61–75.

Reichert, R.D., Tatarynovich, J.T., Tyler, R.T., 1986. Abrasive dehulling of quinoa (*Chenopodium quinoa*): effect on saponin content was determined by an adapted hemolytic assay. Cereal Chem. 63, 471–475.

Repo-Carrasco, R., Espinoza, C., Jacobsen, S.E., 2003. Nutritional value and use of the Andean crops quinoa (*Chenopodium quinoa*) and kañiwa (*Chenopodium pallidicaule*). Food Rev. Int. 19 (1–2), 179–189.

Risi, J., Galwey, N.W., 1984. The *Chenopodium* grains of the andes: inca crops for modern agriculture. Adv. Appl. Biol. 10, 145–216.

Risi, J., Galwey, N.W., 1989a. Chenopodium grains of the Andes: a crop for the temperate latitudes. In: Wickens, G.E., Haq, N., Day, P. (Eds.), New Crops for Food and Industry. Chapman and Hall, New York.

Risi, J., Galwey, N.W., 1989b. The pattern of genetic diversity in the Andean grain crop quinoa (*Chenopodium quinoa* Willd.). I. Association between characteristics. Euphytica 41, 147–162.

Risi, J., Galwey, N.W., 1991. Genotype × environment interaction in the Andean grain crop quinoa (*Chenopodium quinoa*) in temperate environments. Plant Breed. 107 (1), 141–147.

Rojas, W., Barriga, P., Figueroa, H., 2003. Multivariate analysis of genetic diversity of Bolivian quinoa germplasm. Food Rev. Int. 19 (1–2), 9–23.

Ruales, J., Nair, B.M., 1992. Nutritional quality of the protein in quinoa (*Chenopodium quinoa* Willd) seeds. Plant Foods Hum. Nutr. 42, 1–12.

Ruales, J., Grijalva, Y., Jaramillo, P.L., Nair, B.M., 2002. The nutritional quality of an infant food from quinoa and its effect on the plasma level of insulin-like growth factor-I (IGF-I) in undernourished children. Int. J. Food Sci. Nutr. 53 (2), 143–154.

Ruas, P.M., Bonifacio, A., Ruas, C.F., Fairbanks, D.J., Anderson, W.R., 1999. Genetic relationships among 19 accessions of six species of *Chenopodium* L. by random amplified polymorphic DNA fragments (RAPD). Euphytica 105 (1), 25–32.

Schlick, G., Bubenheim, D.L., 1996. Quinoa—Candidate Crop for NASA's Controlled Ecological Life Support Systems. In: Janick, J. (Ed.), Progress in New Crops. ASHS Press, Arlington, VA.

Schulte-auf'm-Erley, G., Kaul, H.P., Kruse, M., Aufhammer, W., 2005. Yield and nitrogen utilization efficiency of the pseudocereals amaranth, quinoa and buckwheat under differing nitrogen fertilization. Eur. J. Agron. 22 (1), 95–100.

Silvestri, V., Gil, F., 2000. Alogamia en quinua. Tasa en Mendoza (Argentina). Revista de la facultad de Ciencias Agrarias. Universidad Nacional de Cuyo 32 (1), 71–76.

Simmonds, N.W., 1965. The grain chenopods of the tropical American highlands. Econ. Bot. 19, 223–235.

Simmonds, N.W., 1971. The breeding system of *Chenopodium quinoa*. I. Male sterility. Heredity 27, 73–82.

Soliz-Guerrero, J.B., Jasso de Rodriguez, D., Rodriguez-Garcia, R., Angulo-Sanchez, J.L., Mendez-Padilla, G., 2002. Quinoa saponins: concentration and composition analysis. In: Janick, J., Whipkey, A. (Eds.), Trends in New Crops and New Uses. ASHS Press, Alexandria, VA, pp. 110–114.

Swinkels, J.J.M., 1985. Sources of starch, its chemistry and physics. In: Van-Beynum, G.M.A., Roels, J.A. (Eds.), Starch Conversion Technology. Marcel Dekker, New York, pp. 15–46.

Tapia, M.E., 1979. Historia y Distribucion geographica. Quinua y Kaniwa. Cultivos Andinos. In: Tapia, M.E. (Ed.), Serie Libros y Materiales Educativos, vol. 49. Instituto Interamericano de Ciencias Agricolas, Bogota, Colombia, pp. 11–15.

Tapia, M., 1982. The Environment, Crops and Agricultural Systems in the Andes and Southern Peru. IICA.

Tomlinson, S.A., Faithfull, E.M., Webb, M.J.W., Fraser, R.S.S., Primrose, S.B., 1981. Isolation and characterisation of a new soil-borne virus. 31st Annual Report for 1980. National Vegetable Research station, Wellesbourne, Warwickshire, UK. pp. 87–88.

Vacher, J.J., 1998. Responses of two main Andean crops, quinoa (*Chenopodium quinoa* Willd.) and papa amarga (*Solanum juzepczukii* Buk.) to drought on the Bolivian Altiplano: significance of local adaptation. Agr. Eco. Environ. 68, 99–108.

Van Etten, C.H., Miller, R.W., Wolff, I.A., Jones, Q., 1963. Amino acid composition of seeds from 200 angiosperm plants. J. Agric. Food Chem. 11, 399–410.

Ward, S.M., 1998. A new source of restorable cytoplasmic male sterility in quinoa. Euphytica 101, 157–163.

Ward, S.M., 2000. Response to selection for reduced grain saponin content in quinoa (*Chenopodium quinoa* Willd.). Field Crops Res. 68 (2), 157–163.

Ward, S.M., Johnson, D.L., 1993. Cytoplasmic male sterility in quinoa. Euphytica 66, 217–223.

Ward, S.M., Johnson, D.L., 1994. A recessive gene determining male sterility in quinoa. J. Hered. 85, 231–233.

White, P.L., Alvistur, E., Dias, C., Vinas, E., White, H.S., Collazos, C., 1955. Nutrient content and protein quality of quinoa and canihua, edible seed products of the Andes mountains. J. Agr. Food Chem. 3, 531–534.

Wilson, C., Read, J.J., Abo, K.E., 2002. Effect of mixed-salt salinity on growth and ion relations of a quinoa and a wheat variety. J. Plant Nutr. 25 (12), 2689–2704.

Wilson, H.D., 1980. Artificial hybridization among species of *Chenopodium* sect. Chenopodium. Syst. Bot. 5, 253–263.

Wilson, H.D., 1988a. Allozyme variation and morphological relationships of *Chenopodium hircinum* Schrader (s. lat.). Syst. Bot. 13, 215–228.

Wilson, H.D., 1988b. Quinua biosystematics I. Domestic populations. Econ. Bot. 42, 461–477.

Wilson, H.D., 1990. Quinua and relatives (*Chenopodium* sect. Chenopodium subsect. Cellulata. Econ. Bot. 44, 92–110.

Wright, K.H., Huber, K.C., Fairbanks, D.J., Huber, C.S., 2002a. Isolation and characterization of *Atriplex hortensis* and sweet *Chenopodium quinoa* starches. Cereal Chem. 79 (5), 715–719.

Wright, K.H., Pike, O.A., Fairbanks, D.J., Huber, C.S., 2002b. Composition of *Atriplex hortensis*, sweet and bitter *Chenopodium quinoa* seeds. J. Food Sci. 67 (4), 1383–1385.

Zanabria, E., Mujica, S.A., 1977. Plagas de la quinua. Curso de Quinua, Fondo Simon Bolivar, Ministerio de Alimentacion. Instituto Interamericano de Ciencias Agricolas, Universidad Nacional Tecnica del Altiplano, Puno, Peru, pp. 129–142.