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Emerging Research in Alternative Crops

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Emerging Research in Alternative Crops

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Foreword

The global population is expected to increase to 9.7 billion in 2050, and there are concerns about the capacity of agriculture to produce enough food for the growing population. By some estimates, food production will need to go up by about 60% either through increase in crop yields per unit area or expansion in the arable land by 2050 to meet the demand (World Population Prospects—the 2008 Revision, UN, 2009). Furthermore, several regions already suffering from malnutrition, water scarcity, and soil degradation have been forecast to have a large population growth which raises serious concerns about whether traditional agricultural methods and crop species will have the capacity to sustain global food production targets.

Major cereal crops like wheat, rice, barley, and corn are progressively failing to withstand increasing salinity and scarce water resources in marginal environments that are most vulnerable to climate change. Therefore, there is an urgent need to identify alternative solutions to sustaining and, possibly, increasing agricultural productivity in areas where growing traditional crops has become difficult and sometimes uneconomical. Therefore, it is important to shift the focus to highly nutritious and resilient crops. But it is also necessary to create sustainable value chains for these non-staple crops to ensure higher incomes for smallholder producers.

To achieve SDGs 1 and 2 which call for no poverty and zero hunger, we will have to transform our agricultural systems to be more efficient and benefit more farmers. One of the strategies is to diversify and reinvigorate the system through alternative crops that can withstand vagaries of climate and address hunger, malnutrition, and poverty.

Recognizing alternative crops' potential for marginal environments, ICBA has been leading a global research program on alternative crops since its creation in 1999 in collaboration with national, regional, and international research, government, and donor organizations in Africa, NENA region, as well as Central Asia. Mohammed VI Polytechnic University (UM6P) is a new institution that aims to promote research and development in several sectors in Morocco and Africa including agriculture and has recently launched a series of programs focusing on alternative crops' introduction, development, and valorization such as quinoa and salt-tolerant forage crops with many partners including OCP, Phosboucraa Foundation, IDRC-Canada, etc.

Alternative crops such as quinoa can play an important role in eradicating hunger, malnutrition, and poverty; furthermore, quinoa has an important nutritional value—the seeds are rich in essential amino acids and vitamins. Due to its adaptability to harsh environments including poor saline soils with annual rainfall as little as 200 mm, quinoa and other alternative crops could play a major role as alternative staple crops in marginal environments

Despite the growing global recognition of alternative crops potential, and positive research outcomes in pilot studies, there are still many constraints and issues to be addressed before those crops become a choice in marginal areas where other major crops have so far been dominant but are now failing due to climate change and degradation in the quality of soil and water resources.

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Preface

Many regions in the world are suffering from water scarcity, soil and water salinization, and climate change which make it difficult to achieve food security by cultivating the conventional crops. A renaissance of interest in cultivating alternative crops (quinoa, amaranth, etc.) is occurring, primarily among small-scale producers, researchers, and academicians especially under water scarcity and salinity conditions. The incorporation of alternative crops may provide environmental benefits such as salt-affected soil cleaning, reduced pesticide use, enhanced soil and water quality, promotion of wildlife diversity, as well as economic benefits including the opportunity for producers to take advantage of new markets and premium prices, to spread economic risk, and to strengthen local economies and communities. Furthermore, alternative crops are often rich in proteins and minerals and even some of them are gluten free (e.g., quinoa) which reflect their importance in achieving food security in quantity and quality scale. The year 2013 was an exceptional one for alternative crops as it was the international year of quinoa celebrated by Food and Agriculture Organization (FAO) which indicates the massive amount of research conducted on quinoa and other alternative crops in many regions of the world.

This book aims to be an essential reference source about new crop cultivation and cropping systems in many places of the world and to be a beginning of new emerging research topics in order to treat all related aspects of adaptation including agricultural, environmental, biological, and socioeconomic issues. It is hoped that this book will provide operational and practical solutions for scientists, producers, technology developers, and managers to succeed new alternative crops' introduction and consequently to achieve food security.

This book is structured into main three sections, covering a wide range of topics related to alternative crops. The first section tackles the generalities, importance, adaptation of alternative crops in general under marginal environment, and their roles in achieving food security and valorizing marginal soils and waters. The second focuses on quinoa crop given its importance and the worldwide interest it attracts. This section provides detailed analysis of quinoa behavior and responses under various stresses (salinity, drought, heat) focusing on its agronomic and physiological responses. The third section presents specific case studies of several researches conducted on other alternative crops showing their agronomic, environmental, and nutritional importance and their adaptation under various marginal environments.

We hope that the book will be of interest to a wide audience involved in alternative crops, researchers, farmers and producers, academicians, advanced-level students, technology developers, socioeconomics, dietitians, and agriculture extension services. And we wish they will find this text useful in furthering their research exposure to pertinent topics in new alternative crops' introduction and adaptation.

Finally, we would like to thank all the authors of this book for their time and effort in preparing this comprehensive compilation of research papers.

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This book is the result of collective efforts of scientists from different regions working on alternative crops. We thank them all for their contribution and their time and patience. Our gratitude extends to the International Center for Biosaline Agriculture (ICBA) and Mohammed VI Polytechnic University (UM6P) for financially supporting this book with special thanks to Dr. Ismahane Elouafi, ICBA D.G., and Mr. Hicham El Habti, S.G. of UM6P, for their continuous support and encouragement.

Finally, the team would like to express appreciation for support received from Dr. Juan Pablo Rodriguez for spending time plowing through various papers.

Contents

Chapter 1
The Contribution of Alternative Crops to Food Security in Marginal Environments

Ismahane Elouafi, Mohammed Ahmed Shahid, Abdumutalib Begmuratov, and Abdelaziz Hirich

Abstract This chapter elucidates the importance of alternative crops in achieving food security in marginal environments. It also presents an overview of marginal environments and alternative crops and highlights the tolerance of the latter to abiotic stresses. The chapter focuses on the experience of the International Center for Biosaline Agriculture (ICBA) in genetic improvement and selection of alternative crops as well as conservation of genetic resources. Finally, it proposes the way forward for improving the productivity of alternative crops and their adaptation in marginal environments, elaborates on ICBA's strategy in this regard, highlights some of the other international efforts, and emphasizes the need for enhanced scientific collaboration and capacity building of farmers and other stakeholders in marginal environments.

Keywords Quinoa · productivity · salinity · drought · forage crops

1.1 Introduction

1.1.1 Marginal Environments

Environments can be marginal either as far as the biophysical aspects are concerned or in terms of their capacity to sustain socioeconomic activities (or of course both). An extreme example of the former is the Empty Quarter of the Arabian Peninsula, where in the absence of water, there is practically no biotic activity. An example of the latter is the "slash and burn" farming systems in tropical rainforests, which yield

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low returns to farmers, but when undertaken through traditional farming practices, create different areas at different stages of a natural regeneration process. These two examples may appear marginal from one lens but sustainable from another. Likewise, a barren desert of sand dunes supports flora and fauna that is sustainable in the sense of being adapted to low water availability, while a low productivity farming system in the tropical rainforest mimics the local ecosystem in terms of regenerating nutrient cycles and supporting biodiversity.

Marginal areas are therefore an integral component of the overall ecosystem of humans, plants, and animals interacting with land, water, and climate variables. The continuum of natural resources from high potential regions to marginal zones is affected by the interaction among its components, which are themselves constantly in a state of change. Some productive areas can be transformed into marginal areas by poor resource management, such as the case of salinization of irrigated lands in Central Asia, Iraq, and Pakistan. There are also are examples of marginal regions being transformed into production zones through smart investments (such as tile drainage in the Egyptian delta), drip irrigation (throughout the Middle East and North Africa), and treated urban wastewater reuse (UAE, Jordan, Tunisia). These examples, all of which combine appropriate applications of science and technology with substantial investments of public and private financial resources, have expanded irrigation on large tracks of semi-arid zones and desert regions in South and East Asia, in the Middle East and North Africa, and Central Asia.

The CGIAR report (CGIAR 2000) describes marginal agricultural lands that are used for agriculture, grazing, or agroforestry as typically encompassing mountains and tropical and subtropical lowlands or plateau, with poor soils and low fertility, with low quality and quantity of water, and with unstable rainfall, or higher rainfall areas in intensive use relative to use-capability under existing population densities, traditional technologies, and institutional structures. In most cases, in the absence of external inputs, and due to disruption of institutions safeguarding common property resources, these marginal areas have reached or exceeded the threshold limits to maintenance or enhancement of agricultural performance.

According to the FAO typology, prime land is capable of producing 80% of potential attainable yields for a basket of crops. Good land may produce 40–80% of potential yields. Marginal land produces less than 40% of yield potential. A FAO study (FAO 2011) concluded that the highest proportion of prime lands currently cultivated is found in Central America and the Caribbean region (42%), followed by Western and Central Europe (38%), and North America (37%). In the Middle East and Central Asia, the share of cultivated prime or good land is well below 28%, implying that there is a much greater dependence on marginal resources.

Figure 1.1 classifies regional lands in terms of favored and marginal status, based on the land and water resources that each represents, utilizing information available in the Aqueduct database (http://www.wri.org/our-work/project/aqueduct). The areas in brown represent marginal lands constrained by either lack of water resources or poor quality of soils, while gray areas have currently zero economic use for agriculture and livestock because they represent deserts, rocky soils, etc.

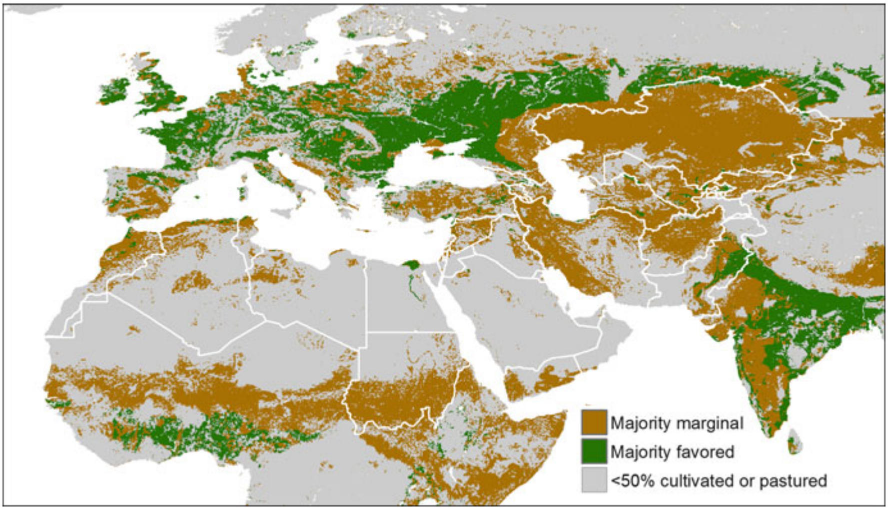

Fig. 1.1 Classification of land using FAO categories of favorable and marginal lands

1.1.2 Alternative Crops

Crop diversification is a key tenet of sustainable farming. Access to diversified crops that fill distinct niches in an agroecosystem improves the ability to manage weeds, pests, and diseases, as well as potentially improving the environmental and agronomic performance of the cropping system. Research activities can help overcome production and market obstacles by developing good cropping practices that enable the successful introduction of alternative crops (Sauer and Sullivan 2000). Alternative crops are crops introduced to a new environment to replace cultivated traditional crops and overcome production constraints caused by biotic stresses (salinity, drought, heat, etc.) or abiotic stresses (pests, diseases, etc.). These crops are usually grown in small areas and their products have niche markets. In another definition by Isleib (2012), an alternative crop is an agronomic crop not usually grown in a particular geographic area, but selected for use due to potential high sale value or specialized benefit to the farming system, which may involve both risks and opportunities. A crop can be very common in one geographic area and considered an alternative in another.

Some examples of alternative crops are presented in Table 1.1:

- *Comparative advantages of alternative crops versus traditional crops*

Various factors have stimulated interest in crop diversification in recent years: commodity price instability, decreased or eliminated farm subsidies, increased pesticide resistance in pests, and losses in genetic biodiversity. At the same time, consumer dietary changes have generated new markets for alternative food products (Toader et al. 2011). Diversification through introduction of new alternative cropping systems reduces risk (related to abiotic and biotic stress, particularly in

Table 1.1 Some alternative crops (but not limited to!)

Category	Crops
Cereals and pseudocereals	Amaranth, blue corn, buckwheat, einkorn, emmer, foxtail, grain millet, khorosan wheat, intermediate wheatgrass, pearl millet, quinoa, spelt, teff, triticale, wild rice, reed canary grass, halophytic grass, canihua
Grain legumes	Many varieties of dry beans and dry peas, Illinois bundleflower, lentils, *lupinus*, cowpea, pigeon pea, *sesbania*, guar
Oilseeds	Apeacia, camelina, canola, crambe, rape, cuphea, jojoba, lesquerella, meadowfoam, perilla, rapeseed, sesame, flax, sunflower, safflower, mustard, salicornia
Industrial crops	Bladder pod, castor, cuphea, euphorbia, fanweed, gopher plant, guayule, gumwood, jojoba, lesquerella, vernonia, stevia, jatropha
Fiber crops	Kenaf, milkweed, flax

fragile ecosystems, and commodity fluctuations), contributes to improved food security and income of poor farmers, and protects the environment. Small family farms cannot increase their total income to acceptable levels by producing staple food crops alone, as these are invariably of low value to the farmers/producers (e.g., cereals). To increase income, farmers need to adopt new crops with a high value and high tolerance to adverse stresses (e.g., quinoa). Fruits, vegetables, herbs and spices, flavorings, natural colorants, medicinal plants, and others all offer an opportunity for farmers to produce higher-value products. However, the introduction of new crops must be accompanied by an integrated technological and commercial package in order to ensure successful adoption by farmers (Duwayri 2001).

Intensive production of traditional crops was practiced only at the level of species until about 100 years ago, with, for example, wheat, maize, or rice becoming dominant in different climatic regions. Monoculture has since expanded to different levels, reducing the numbers of species, of varieties within species, and particularly of genetic differences within varieties (Wolfe 2000). However, as rising demands for agricultural products continue to lead to further crop intensification, monocultures have increased dramatically worldwide, where the same crop (usually corn, wheat, or rice) is grown year after year in the same field, or simple crop rotations are adopted. There are many problems associated with the increasing extent of monoculture, including the simplification of cropping systems devoted to a single crop variety (Altieri 1998), soil degradation due to missuse of chemical inputs (Bramley et al. 1996), development of emerging diseases and pests (Shipton 1977), vulnerability to climate change (Chakraborty and Newton 2011), loss of nutritional value and food safety (Frison et al. 2011), etc.

Negative environmental impacts have to be minimized through diversification of cropping systems and agricultural practices (Bommarco et al. 2013). Alternative cropping systems commonly support high degree of plant diversity in the form of polycultures and/or agroforestry patterns. The strategy of planting several species of plants and varieties of crops minimizes risks associated with crop failure, stabilizes yields over the long term, promotes diet diversity, and maximizes returns even with low levels of technology and limited resources such as those in marginal environments (Altieri 2002).

The combination of water scarcity, climate change and variability, and increasing population that marginal environments are facing paints a gloomy picture of their future food security and explains the rising interest in alternative crops. Due to a variety of factors, alternative crops have evolved to become adapted to adverse environmental conditions such as drought and salinity stress. In view of this, they have an important role to play as potential future crops that can ensure food security in marginal environments (Chivenge et al. 2015). In addition to their adaptation to diverse ecological niches, most alternative crops have shown to be highly nutritious and, in some cases, to have medicinal properties. For example, quinoa is a high-value crop that has double the protein content of wheat.

In order for alternative crops to play key roles in sustainable farming in marginal environments, there is a need to develop efficient value chains for such crops, spanning from field production to marketing (Thompson et al. 1993). Value chains for alternative crops need to be agronomically and genetically developed so as to make them commercial products that can be traded not only on the local market but also internationally. This means that there is also a need to increase the demand for products deriving from alternative crops. In summary, sustainability of alternative crops requires concerted efforts directed at conservation of the genetic resource base, its genetic improvement, value chain development, and promotion of increased utilization.

1.2 Tolerance of Alternative Crops to Abiotic Stresses

Scientists report that using alternative sources like brackish and saline water to meet the needs of agriculture is a one way to reduce the pressure on freshwater. This means it is essential to shift the focus from salt-sensitive forage crops that are widely cultivated for livestock feed to salt-tolerant or halophytic crops.

Alternative crops are called so because they are cultivated to replace traditional crops when the productivity and performance of the latter is affected by stresses, or introduced to new environments where other crops cannot be grown at all. In fact, most of the alternative crops have important traits related to abiotic stress tolerance. A good example of this are halophytes crops, defined as a kind of native flora of saline soils, which contain solutions with a Psi of at least 3.3 bar, being equivalent to 70 mM monovalent salts (Greenway and Munns 1980). *Salicornia*, for example, is a halophyte that can be grown with seawater and used for biofuel (derived from seeds) and animal feed (using vegetable and residual biomass). Cultivation of *Salicornia* has achieved different degrees of success in different parts of the world. Some *Salicornia* species are being farmed on a commercial scale for biodiesel, animal feed, and salt and oil extraction, e.g., *S. bigelovii* (Patel 2016). This species produces oleaginous seeds which have been evaluated as promising feedstock for biodiesel production (Eganathan et al. 2006). Among the wide diversity of existing halophyte species, those with the greatest economic potential as crops will contribute to the most promising strategies for sustainable agriculture in marginal environments. Ventura and Sagi (2013) listed halophyte plants with the highest potential as vegetable crops utilizing saline irrigation with a salt tolerance level (i.e., salinity level in the irrigation solution that results in a 50% reduction in yield) exceeding 100 mM, including *Salicornia* and *Atriplex* species.

Another example of an alternative crop that can tolerate various stresses and which has attracted significant attention in the last decade is quinoa. Quinoa was subjected during the beginning of this century to a large number of researches in all parts of the world, including the Gulf Cooperation Council (GCC), which is characterized by a harsh climate, excessive heat, and water scarcity (Choukr-allah et al. 2016). Quinoa has been shown to be resistant to various abiotic stresses, including water scarcity (Fghire et al. 2015; Hirich 2013; Hirich et al. 2013; Hirich et al. 2012; Geerts et al. 2009; Geerts et al. 2008; Filali et al. 2017), salinity (Hirich et al. 2014b; Hirich et al. 2014c; Koyro et al. 2008; Eisa et al. 2012; Koyro and Eisa 2008; Razzaghi et al. 2012; Shabala et al. 2013; Yazar et al. 2015; Jacobsen et al. 2000), frost (Bonifacio 2005; Jacobsen et al. 2005; Jacobsen et al. 2007; Winkel et al. 2009), and heat stress (Bazile et al. 2016; Bertero 2001).

Alternative salt-tolerant crops have a great interest and potential to increase crop productivity at farm level when traditional crops become increasingly affected by salinity and therefore uneconomic. A study was performed by Rao et al. (2017) on three abandoned farms due to salinity problem in Abu Dhabi, UAE, to assess the performance of four salt-tolerant perennial grass species irrigated with highly saline water. During 3 years, scientists evaluated the biomass productivity of four grasses, including *Distichlis spicata*, *Paspalum vaginatum*, *Sporobolus virginicus*, and *S. arabicus*, at different water salinity levels varying from 14.1 to 17.4 dS m^{-1}. Biomass was harvested three times a year and reached 32.64–40.68 tonnes per ha per year of dry biomass. The highest biomass yield was recorded for *Sporobolus virginicus*. The study showed that these grasses can perform and grow very well under highly saline water in UAE conditions and therefore, contribute to rehabilitating salt-affected farms.

Drought is one of the major physical phenomena occurring in marginal environments that causes great reductions in crop productivity, particularly in the more arid regions. This problem is expected to worsen in the near future in arid and semi-arid regions, the most affected by the forecasted effects of climate change, which include the occurrence of longer, more frequent, and more intense drought periods (IPCC 2014). Impact of drought or water stress on crop yield depends on stress timing and intensity and the response of the plant (Rauf et al. 2016). Drought stress may occur during the early establishment, vegetative phase, or reproductive phase. Stress application during the reproductive phase generally causes higher yield reduction (Hirich et al. 2014d; Hirich et al. 2014; Hirich and Choukr-Allah 2013).

Generally, species in very arid climates are well adapted to drought stress. Therefore, these species may be recommended for drought-prone environments as a means to increase the area under cultivation and fulfill human food and animal fodder needs. Species in the phase of domestication or semi-domesticated species such as some forages show high genetic variation for drought adaptation and may represent potential candidates for introduction in drought-prone areas (Rauf et al. 2016). Plants showing improved growth under drought conditions are considered to tolerate drought regardless of how the improvement occurs or whether water use efficiency is affected. Some species can avoid drought by maturing rapidly before the onset of dry conditions or by reproducing only after rain (Boyer 1996). One of the alternative crops being developed recently is cactus (*Opuntia ficus-indica*) which is used as a food and feed crop. This crop is relatively drought-resistant, can survive long droughts, and produces large quantities of fodder during the rainy season, which can be utilized during the dry season (Nefzaoui and Ben Salem 2001). Cactus is also used in marginal arid environments to combat desertification, slow and direct sand movement, and enhance restoration of the vegetative cover. Another example of drought alternative crops is *Jatropha curcas*, a soft-woody oilseed that has emerged as a potential source of biofuel. This alternative crop has been described as drought-tolerant and capable of growing in marginal and poor soils (Achten et al. 2010; Maes et al. 2009) and has potential to be cultivated in semi-arid and poor soil conditions without competing with food production for land use (Sapeta et al. 2013).

Another abiotic stress affecting crop growth and productivity in most marginal environments is heat stress. High temperature or heat stress causes an array of morpho-anatomical, physiological, and biochemical changes in plants, which affect plant growth and development and may lead to a drastic reduction in economic yield (Wahid et al. 2007). Heat stress occurs when the ambient temperature exceeds the temperature tolerance threshold, which varies depending on crop types. For example, cotton can resist high temperature up to 45 °C (ur Rahman et al. 2004). Cowpea (Patel and Hall 1990) and pearl millet (Ashraf et al. 1994), which are underutilized alternative crops, tolerate heat with a threshold equal to 41 and 35 °C, respectively.

In addition to genetic means of developing plants with improved heat tolerance, attempts have been made to introduce stress-tolerant crops in desert and arid regions with heat stress conditions especially during the summer season. For example, cactus (*Opuntia ficus-indica*) has been introduced to Rhamna region (Morocco) as a heat- and drought-tolerant alternative to cereals and other traditional crops in order to be used as food and feed crop as well as to protect soils from erosion and desertification (Mazhar et al. 2000). Another example of alternative crops that can be introduced to marginal environments characterized by drought, heat, and salinity is quinoa. This crop has been introduced to many areas in the past years, including North Africa (Benlhabib et al. 2014; Lavini et al. 2014), Sub-Saharan Africa (Bazile et al. 2016a), Central Asia (Choukr-allah et al. 2016), Middle East (Choukr-allah et al. 2016), etc.

1.3 The Experience of the International Center for Biosaline Agriculture (ICBA) in Genetic Improvement and Selection of Alternative Crops

1.3.1 Alternative Crops Researched at ICBA

Crop diversity plays a major role in sustainable agriculture. Multiple crops help to withstand biotic and abiotic threats to agricultural productivity. Given the importance of alternative crops, ICBA has embarked on a program to collect, conserve, and evaluate different crops considered to be drought-, salinity-, and heat-tolerant. The other aim of ICBA's work is to study their adaptability and yield potential so that they can be introduced as alternative crops to the farmers of the Arabian Peninsula, Africa, and other regions with similar climatic conditions.

The following are some of the alternative crops that have been studied at ICBA for their tolerance against various abiotic stresses as well as adaptability to the region:

1.3.1.1 Quinoa (*Chenopodium quinoa* Willd.)

It is an annual herbaceous plant, which is a pseudo-cereal cultivated in South America for thousands of years for its wholesome grain. Quinoa plants grow best in sandy, well-drained soils with little nutrients and a pH of 6–8.5. It is a hardy crop that tolerates drought and salinity, which makes it important for diversification of future agricultural systems in the Arabian Peninsula and elsewhere.

Different studies have been conducted at ICBA's experimental station in Dubai, UAE, to test its salinity tolerance as well as adaptability to the region. In one of the investigations, a number of quinoa cultivars were tested for different yield-related traits when cultivated in a sandy soil and hot environment (Rao and Shahid 2012). In another study, various accessions of the crop were grown in different regions of the world to explore their adaptation and tolerance against salinity (Choukr-allah et al. 2016). All of these investigations confirmed that quinoa can be cultivated as an alternative crop in the regions with salinity problems. In a large comprehensive research in collaboration with King Abdullah University of Science and Technology (KAUST), Saudi Arabia, more than 1400 quinoa accessions are being studied to analyze salinity tolerance at genetic and molecular level.

1.3.1.2 *Salicornia* (*Salicornia bigelovii* Torr.)

Salicornia is a halophytic annual plant with succulent photosynthetic stems found in seashore regions and salt pans of the northwestern Mexico (Rodríguez-Medina et al. 1998; Rueda-Puente et al. 2007). Different studies show that it has an enormous potential as an oilseed and forage crop for the coastal areas of deserts and wastelands, using seawater for irrigation (Glenn et al. 1991; Glenn et al. 1992).

At ICBA, various studies were carried out to find its potential as an oilseed, forage, and vegetable crop. In one experiment, five salicornia lines were grown using seawater to investigate their performance as fodder and oilseed (Shahid et al. 2013). In other study, breeding populations were evaluated for phenotypic, morphometric, biomass, and seed traits in order to select and develop the best genotypes for biomass, seed, and vegetable production when cultivated in marginal lands using sea and brackish water (Jaradat and Shahid 2012). The results indicate that the salicornia lines can be used by farmers as an alternative crop for vegetable and oilseed production.

1.3.1.3 Cowpea (*Vigna unguiculata* (L.) Walp.)

Cowpea is a legume crop, which is an important part of the conventional cropping systems in semi-arid tropical regions around the world. Being a leguminous plant, it fixes nitrogen in its roots and hence enhances soil fertility. Cowpea is a multipurpose crop, as its young leaves, green pods, and green seeds are used as vegetables, while its dry seeds are also consumed in different ways (Singh et al. 2003). Different studies indicate that cowpea is a salt-, drought-, and heat-tolerant crop (Win and Oo 2015; Bastos et al. 2011; Craufurd et al. 1998) and as such an ideal alternative crop for the marginal lands.

An experiment comprising 23 cowpea cultivars was conducted during summer at ICBA to assess their performance as a vegetable, forage, and grain crop when cultivated at high temperature (Rao and Shahid 2011). The results showed that it can be grown as a multipurpose crop with less amount of irrigation water at high temperature than other crops that need much more water to achieve optimum yield. The study recommends cowpea as an alternative multiuse crop for the UAE and other countries with similar climate and soils.

1.3.1.4 Guar (*Cyamopsis tetragonoloba* (L.) Taub.)

Guar is an annual legume cultivated in parts of Asia as a vegetable, forage, and seed crop. The guar seed has a large endosperm that contains galactomannan gum, which is used in food and other industries (Undersander et al. 1991). Being tolerant to salinity and drought (Rasheed et al. 2015; Ray and Livingston 1986), guar is suitable as a cash crop for marginal lands with salinity and drought problems.

To assess its potential as an alternative crop in the Arabian Peninsula, ICBA conducted a field experiment containing ten guar accessions. Different agronomic and morphological characteristics of the plant were studied at various stages. The results confirmed that guar can be planted in the region as a seed, vegetable, and fodder crop (Rao and Shahid 2011).

1.3.1.5 Safflower (*Carthamus tinctorius* L.)

It is an herbaceous annual crop, which is cultivated in different parts of the world mainly as an oilseed crop, but also for fodder, floriculture, and birdseed. Safflower is a resilient plant that can withstand drought and salinity (Khalili et al. 2014; Hussain et al. 2016) and can therefore be cultivated as an alternative crop in marginal lands that face water shortages or salinity problems.

ICBA carried out research on about 630 safflower accessions from 11 countries to study 16 different morphological and agronomic traits that are desirable to farmers (Jaradat and Shahid 2006). The germplasm carries a large amount of variation to contribute toward suitable plant morphology to breed new safflower varieties suitable for different growing environments in the Arabian Peninsula. It is anticipated that these accessions will help in sustainable production of seed, fodder, and ornamental plants in the hot climate and short cropping season of the region and other areas around the world with similar climatic conditions. In another experiment at the Center, different safflower genotypes were grown under different salinity levels to study crop tolerance to salt. The investigation revealed that some of the cultivars are more salt-tolerant than others.

1.3.1.6 Mustard (*Brassica juncea* (L.) Czern.)

It is an annual winter crop with edible leaves, seeds, and stems, mostly grown as an oilseed and condiment crop. Mustard greens are among the healthiest vegetables because of high concentration of many flavonoids (Ambrosone and Tang 2009). Mustard plants can also be used as fodder and to produce green manure to enhance the fertility of agricultural soils. The crop is considered to be relatively drought- and salinity-tolerant (Sharma et al. 2013; Ashraf and McNeilly 2004), which makes it suitable for cultivation in the regions with those abiotic stresses.

At ICBA, yield trials were conducted using ten mustard accessions to evaluate their adaptability to the region (Rao et al. 2009). Performance of the genotypes was assessed by recording data on their different agronomic characteristics. The results were encouraging as most of the cultivars produced good yield for both seed and plant mass. These findings confirm that mustard can be cultivated successfully as an alternative crop in the arid regions of the Arabian Peninsula.

1.3.1.7 Pigeon pea (*Cajanus cajan* (L.) Millsp.)

It is a perennial legume that was domesticated about 3500 years ago. Pigeon pea seeds, which are rich in protein, are used as food grain mainly in South Asia and some other regions of the world. The plant is also used for green manure, adding up to 90 kg nitrogen per hectare (Adu-Gyamfi et al. 2007). Its woody stems can also be used as fuel, thatch, and fencing. It is a drought-tolerant crop that can be cultivated in dry areas with little water for irrigation (Mathews and Saxena 2005). The crop has also shown tolerance against salt at its different stages of growth (Ashraf 1994).

Some experiments were carried out at ICBA field research facilities to evaluate pigeon pea as an alternative crop for the region (Rao et al. 2009). The results demonstrated the good adaptation of the crop and hence its high potential to be a part of crop diversification in the Arabian Peninsula.

1.3.1.8 Colocynth (*Citrullus colocynthis* (L.) Schrad.)

It is a perennial desert vine that grows well in sandy, arid soils. It is a highly drought-tolerant plant, which is usually used for its medicinal properties. Since the plant has the potential for high yields of oilseed, it can be planted on marginal lands to produce cheap biofuel (Giwa et al. 2010). With a high seed oil content (53%), it can produce up to 3 $T.ha^{-1}$ of oil, which is more or less equal to other key oilseed crops. Its oil can also be consumed like regular vegetable oils.

To explore the possibility of using local colocynth as an oilseed crop, research was carried out to collect and analyze the genotypes of wild species from different parts of the UAE ((Shahid and Rao 2014). Twenty-five different colocynth ecotypes were collected to study eight morphological parameters, including fruit length and diameter, number of seeds per fruit, seed length, seed width, seed thickness, 100-seeds weight, and seed weight per fruit. The study showed the presence of large variation in fruit and seed traits among the collected colocynth accessions. Some of the genotypes have shown good potential for cultivation as an oilseed crop in the sandy soils with little irrigation.

1.3.2 ICBA's Gene Bank of Alternative Crops

ICBA has collected and conserved thousands of accessions of various alternative crops at its facilities (Table 1.2). The seeds of important alternative crops are multiplied at its experimental field and stored in the gene bank.

ICBA is also supporting stakeholders of crop diversification in different regions of the world through provision of seeds of alternative crops. So far, the Center has distributed more than 3500 seed samples of alternative crops to various research organizations, private seed companies, and farmers in the UAE and other countries around the world (Table 1.3).

1.4 How Alternative Crops Can Contribute to Food Security

- Meeting the food requirements of the burgeoning global population

By 2050, the world's population will reach 9.1 billion, 34 percent higher than today. Nearly all of this population increase is expected to occur in developing countries. Ensuring that that there will adequate food for all is one of this century's most pressing and daunting challenges, especially in light of the fact that in 2016 an estimated 815 million people—just over one in nine—were undernourished due to inadequate access to food (FAO et al. 2015). The increased demand for food and animal feed will require an increase of 70 percent in global food production by 2050 (FAO 2009). There is, therefore, a need to bring marginal lands into production and/or to increase their productivity in order to ensure global food security and the achievement of Sustainable Development Goal 2 (Zero Hunger). Alternative crops that can thrive in marginal conditions offer a sustainable solution to this challenge.

Table 1.2 Seeds of different alternative crops in the ICBA gene bank

Crop	Species	Family	Category/uses	# of accessions
Amaranth	*Amaranthus* sp.	Amaranthaceae	Fodder	49
Atriplex	*Atriplex* sp.	Amaranthaceae	Fodder	40
Buffelgrass	*Cenchrus ciliaris*	Poaceae	Fodder	820
Canola	*Brassica napus*	Brassicaceae	Oilseed, fodder	99
Castor	*Ricinus communis*	Euphorbiaceae	Oilseed	11
Colocynth	*Citrullus colocynthis*	Cucurbitaceae	Oilseed	27
Cowpea	*Vigna unguiculata*	Fabaceae	Grain, fodder, vegetable	48
Guar	*Cyamopsis tetragonolobus*	Fabaceae	Fodder, gum, vegetable	99
Jujube	*Ziziphus spina-christi*	Rhamnaceae	Fruit	6
Lablab	*Lablab purpureus*	Fabaceae	Grain, fodder, vegetable	44
Lupin	*Lupinus* sp.	Fabaceae	Grain, fodder	217
Mustard	*Brassica juncea*	Brassicaceae	Oilseed, fodder, vegetable	100
Pigeon pea	*Cajanus cajan*	Fabaceae	Grain, fodder	137
Purslane	*Portulaca oleracea*	Portulacaceae	Vegetable	3
Quinoa	*Chenopodium quinoa*	Amaranthaceae	Grain, fodder	1050
Safflower	*Carthamus tinctorius*	Asteraceae	Oilseed, fodder, ornamental	630
Salicornia	*Salicornia bigelovii*	Amaranthaceae	Oilseed, fodder, vegetable	12
Sesbania	*Sesbania* sp.	Fabaceae	Fodder, grain	80
Sunflower	*Helianthus annuus*	Asteraceae	Oilseed, ornamental	100
Triticale	Triticale x	Poaceae	Grain, fodder	370

- Mitigating climate change impact on traditional crops

The threat of climate change to food production and food security is nowadays one of the most pressing concerns, exacerbating further the challenge of how to ensure enough food for the growing population by increasing land productivity while conserving the already stressed environment. Agricultural production will be affected by increasing temperatures, changing rainfall patterns, and more frequent and intense extreme weather events (IPCC 2014). These will have direct effects on crop growth and their need for water, as well as soil fertility, water supply for irrigation, and prevalence of pests and diseases. Given that crop production systems worldwide are highly specialized and currently rely on a very small number of species (traditional crops), their sustainability is at risk (De Ron et al. 2017). Climate change has already caused significant impacts on water resources and crop growth and production in marginal environments. As a result, studies on climate change impacts and adaptation and mitigation measures are increasingly becoming major

Table 1.3 Number of alternative crop seed samples supplied to different stakeholders by ICBA

Crop	Species	# of samples	# of stakeholders
Amaranth	*Amaranthus* sp.	19	5
Atriplex	*Atriplex* sp.	6	5
Buffelgrass	*Cenchrus ciliaris*	431	10
Canola	*Brassica napus*	3	1
Colocynth	*Citrullus colocynthis*	19	2
Cowpea	*Vigna unguiculata*	178	32
Guar	*Cyamopsis tetragonolobus*	169	9
Lablab	*Lablab purpureus*	32	8
Mustard	*Brassica juncea*	143	15
Pigeon pea	*Cajanus cajan*	124	10
Quinoa	*Chenopodium quinoa*	1742	63
Safflower	*Carthamus tinctorius*	111	5
Sesbania	*Sesbania sp.*	165	12
Sunflower	*Helianthus annuus*	187	7
Triticale	Triticale x	303	5

areas of scientific concern, particularly impacts on production of traditional crops (Kang et al. 2009). A significant number of studies have been conducted to predict the impact of climate change on wheat (Ludwig and Asseng 2006; Anwar et al. 2007), maize (Jones and Thornton 2003; Conde et al. 1997), rice (Matthews et al. 1997), barley (Trnka et al. 2004), potato (Rosenzweig et al. 1996), and sugar beet (Jones et al. 2003), most of which predicted a reduction in crop yield. Knox et al. (2012) reported changes in the yields of major crops grown across Africa and South Asia under climate change, predicting that average crop yields may decline across both regions (which together include most of the marginal environments on the planet) by 8% by the 2050s. Across Africa, yields are predicted to change by −17% for wheat, −5% for maize, −15% for sorghum, and − 10% for millet, while yields across South Asia are expected to decline by −16% for maize and − 11% for sorghum as a result of climate change. Moreover, a recent study by Hirich et al. (2016) suggested that maize yield could exhibit a reduction of 2.5% toward the end of the twenty-first century as a result of the growth season shortening. Climate change will also have an impact on livestock resources by affecting the quality and amount of feed supply and water.

The future course of global food production will therefore depend on how well farmers can adapt to climate change as well as the influence of other pressures, such as the competition for land from biofuel production. In such conditions, especially those characterized by drought, salinity, and heat, alternative crops that are tolerant to the aforementioned stresses could represent a judicious and practical solution to the negative consequences of a changing climate on food security, especially in marginal environments.

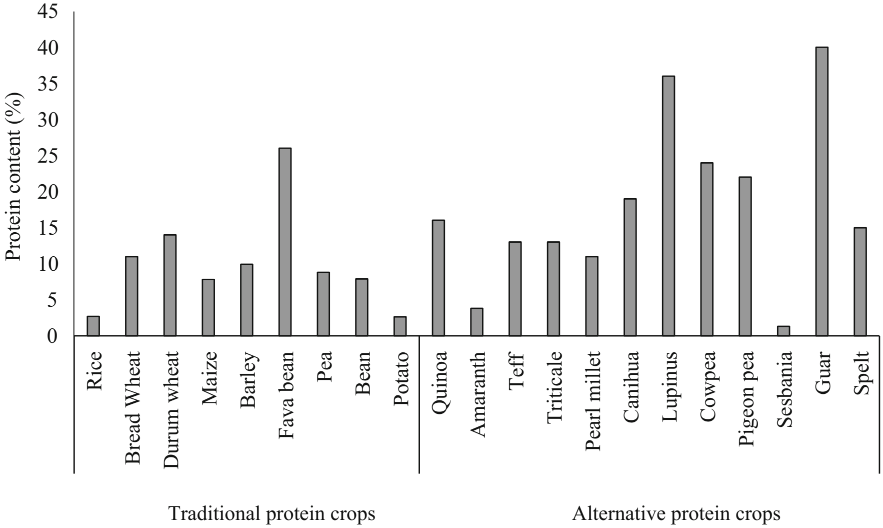

Fig. 1.2 Protein contents (%) of traditional and alternative crops

- Offering high nutritional value

Human food security requires the production of sufficient quantities of both high-quality protein and energy. Because of their high protein content, alternative crops have the potential to satisfy the growing demand for plant protein for food and feed. Figure 1.2 compares the protein content of traditional and alternative crops, underscoring the potential of alternative crops as important sources of protein.

- Offering an alternative source of biofuel

The growth in demand of biofuels in among the factors is responsible for the recent sharp increases in agricultural commodity prices. Biofuels will continue to exert upward pressure on commodity prices, which will have implications for food security and poverty levels, especially in developing countries (Wiebe et al. 2008). Biofuel production exceeds 100 billion liters per year; more than 83% of this quantity consist of ethanol and the rest is biodiesel. In 2008, about 15% of global corn production, equivalent to about 5.7% of the total global coarse grain production, was used to produce ethanol. Moreover, about 10% of global vegetable oil production went to make biodiesel, and 18% of sugar cane went to make ethanol fuel (Afiff et al. 2013). This has serious implications for global food crop production, since a big percentage of fertile and arable lands that were used in the past for food production are now cultivated with biofuel crops.

Figure 1.3 compares the oil content of different traditional and alternative crops and clearly indicates that alternative oil crops have a higher oil content compared to traditional crops. In fact, most of the alternative oil crops that are adaptable to marginal conditions, including salinity and drought, can produce high-quality

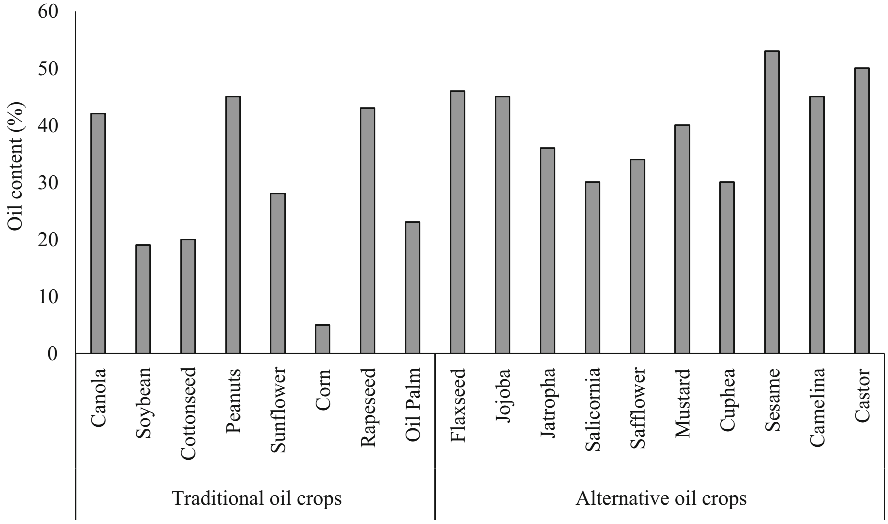

Fig. 1.3 Oil content of traditional and alternative oil crops

biodiesel. Such is the case of jojoba, jatropha, and salicornia, the oils of which have been investigated for potential use as jet fuel (Hendricks 2008; Selim 2009; Verma et al. 2015).

1.5 The Way Forward Toward Improving the Productivity and Adaptation of Alternative Crops in Marginal Environments

- *ICBA's strategy*

Extensive research confirms that alternative crops offer the means for transforming marginal lands into sources of livelihood for rural populations. Not only do these crops do well in unfavorable environmental conditions, but they also help to reduce pressure on natural resources. Their capacity to withstand heat and drought and grow with low-quality and saline water in poor soils makes them a promising solution for agriculture in marginal environments. As monoculture is more failure-prone under marginal conditions, crop diversification offers hope as a measure to mitigate production risks. However, in order for small-scale farmers to adopt alternative crops, the latter need to be not only highly resistant to poor environmental conditions and nutritious but also of high value on the market. These factors guide ICBA's strategy for crop diversification in marginal environments, which comprises the following six steps:

First, the Center focuses its efforts on testing and selecting genotypes of nutritious and stress-tolerant alternative crops. Multi-year and multi-location trials are run before best-performing lines are singled out and made available for seed multiplication and cultivation by farmers.

Second, it works to collect and conserve plant genetic resources of stress-tolerant species from around the world. ICBA's gene bank stores over 12,600 accessions of some 230 plant species with proven or potential salt tolerance from 130 countries and territories.

Third, ICBA conducts social and economic studies on the benefits of cultivating alternative crops in marginal areas. The studies also consider environmental benefits such as improved salinity management, land rehabilitation, and natural resource management.

Fourth, the Center analyzes value chains for alternative crops and looks into their potential for increasing incomes of small-scale farmers. These crops often have niche markets and it is important to link farmers with potential buyers.

Fifth, ICBA develops management practices tailored to different localities. Without adequate knowledge and skills, farmers would fail to achieve desired outcomes. Therefore, the Center works to strengthen the capacity of farmers at all stages, from seed multiplication to cultivation to harvesting.

Sixth, the Center explores how to make use of low-quality water and soil resources to cultivate alternative crops. This effort is aimed at reducing pressure on freshwater resources and favorable soils and in certain cases at rehabilitating degraded natural resources.

Overall, ICBA's strategy is driven by the needs of farmers and the benefits to the environment.

- *International efforts*

Other international organizations also implement programs to study and introduce alternative crops. For example, FAO initiated a technical cooperation project in 2014 to facilitate the introduction of quinoa in the Near East and North Africa. Through this project, FAO has provided technical assistance to organizations in Algeria, Egypt, Iraq, Iran, Lebanon, Mauritania, Sudan, and Yemen in the selection of quinoa genotypes suited to different agro-ecological zones.

In Asia and the Pacific, the International Fund for Agricultural Development (IFAD) has focused on promoting the development and dissemination of sustainable or regenerative agricultural technologies uniquely suited to the complex and diversified agricultural systems of less favored areas.

In Central Asia, ICBA has collaborated with the International Center for Agricultural Research in the Dry Areas (ICARDA) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to implement a program to diversify the variety of crops cultivated by local farmers. The program introduced sorghum and pearl millet in marginal lands in Kazakhstan, Tajikistan, and Uzbekistan in order to improve local livelihoods.

- *Enhance scientific collaboration*

While different programs on crop diversification help to achieve positive outcomes, it is important to enhance interdisciplinary, inter-institutional, and international scientific collaboration. Scientific collaboration is key to the success of efforts to study the benefits of alternative crops and introduce them in marginal environments.

More collaboration will not only accelerate progress but will also enhance the quality of research and development initiatives. It is particularly important given the complexity and scale of challenges in marginal environments.

By working together more closely, research institutions will benefit from sharing knowledge about previous failures and successes in introducing alternative crops in different locations with varying agro-ecological conditions. Scientific partnerships would help to avoid duplication of efforts as well.

Collaborative programs also have higher potential for creating positive impact, more efficiently using resources and harnessing interdisciplinary expertise. As research efforts often focus on only certain aspects of alternative crops, partnerships would facilitate complementarity. Different research institutions would bring to the table specific expertise, experience, technologies, and solutions.

Improved cooperation would also help to address better research funding constraints.

- *Capacity building*

In addition to enhanced scientific collaboration, needs-based capacity development should also take center stage. Institutional and individual capacity-building programs are crucial for technology and knowledge transfer. Introduction of alternative crops requires considerable investments in efforts to build the capacities of in-country research and extension institutions, farmers, and other stakeholders.

It is important to develop and disseminate technology and knowledge packages that are tailored to different groups of stakeholders. With the right knowledge, skills, and technologies, farmers will be more willing to adopt alternative crops. They will also be better able to manage different risks to their agricultural activities. Many international research and development organizations implement programs to this effect. For example, ICBA has invested considerable resources in national capacity development programs in different regions. The Center has trained over 1000 people, including researchers and farmers, on crop diversification and biosaline agriculture technologies in Central Asia, the Middle East, North Africa, and Sub-Saharan Africa. In this regard, there is a need for improved methods of technology dissemination, as the conventional top-down transfer of technology does not work well with complex technologies that must be adapted to local conditions. Future capacity-building approaches should be less capital-intensive, making it possible to reach more stakeholders with fewer resources; for example, they could leverage the boundless potential of information and communication technologies (ICT) to disseminate knowledge among farmers and other stakeholders. In order to ensure complementarities and increase synergies, it is also important to increase coordination and coherence between different institutions on capacity development at national, regional, and international levels.

References

Achten WM, Maes W, Reubens B, Mathijs E, Singh VP, Verchot L, Muys B (2010) Biomass production and allocation in Jatropha curcas L. seedlings under different levels of drought stress. Biomass and Bioenergy 34(5):667–676

Adu-Gyamfi JJ, Myaka FA, Sakala WD, Odgaard R, Vesterager JM, Høgh-Jensen H (2007) Biological nitrogen fixation and nitrogen and phosphorus budgets in farmer-managed intercrops of maize–pigeonpea in semi-arid southern and eastern Africa. Plant Soil 295(1):127–136

Afiff S, Wilkenson J, Carriquiry M, Jumbe C, Searchinger T (2013) Biofuels and food security. A report by the high level panel of experts on food security and nutrition of the committee on world food security

Altieri MA (1998) Ecological impacts of industrial agriculture and the possibilities for truly sustainable farming. Mon Rev 50(3):60

Altieri MA (2002) Agroecology: the science of natural resource management for poor farmers in marginal environments. Agric Ecosyst Environ 93(1):1–24

Ambrosone CB, Tang L (2009) Cruciferous vegetable intake and cancer prevention: role of nutrigenetics. Cancer Prev Res 2(4):298–300

Anwar MR, O'Leary G, McNeil D, Hossain H, Nelson R (2007) Climate change impact on rainfed wheat in south-eastern Australia. Field Crop Res 104(1–3):139–147

Ashraf M (1994) Salt tolerance of pigeon pea (Cajanus cajan (L.) Millsp.) at three growth stages. Ann Appl Biol 124(1):153–164

Ashraf M, McNeilly T (2004) Salinity tolerance in Brassica oilseeds. Crit Rev Plant Sci 23 (2):157–174

Ashraf M, Saeed M, Qureshi M (1994) Tolerance to high temperature in cotton (Gossypium hirsutum L.) at initial growth stages. Environ Exp Bot 34(3):275–283

Bastos EA, SPd N, EMd S, Freire Filho FR, Gomide RL (2011) Identification of cowpea genotypes for drought tolerance. Rev Ciênc Agron 42(1):100–107

Bazile D, Jacobsen S-E, Verniau A (2016) The global expansion of quinoa: trends and limits. Front Plant Sci 7:622

Benlhabib O, Jacobsen SE, Jellen EN, Maughan PJ, Choukr-Allah R (2014) Status of quinoa production and research in Morocco. In: Bazile D (ed) STATE OF THE ART REPORT ON QUINOA around the world in 2013. Food and Agriculture Organization of the United Nations (FAO), Santiago, Chile, pp 178–491

Bertero HD (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

Bommarco R, Kleijn D, Potts SG (2013) Ecological intensification: harnessing ecosystem services for food security. Trends Ecol Evol 28(4):230–238

Bonifacio A (2005) Frost and hail tolerance in quinoa crop and traditional knowledge to handle those adverse factors. In: Jarvis D, Mar I, Sears L (eds) Enhancing the use of crop genetic diversity to manage abiotic stress in agricultural production systems, Budapest, Hungary, 2005. International Plant Genetic Resources Institute, Rome, Italy, pp 68–71

Boyer JS (1996) Advances in drought tolerance in plants. Adv Agron 56:187–219

Bramley R, Ellis N, Nable R, Garside A (1996) Changes in soil chemical properties under long-term sugar cane monoculture and their possible role in sugar yield decline. Soil Res 34(6):967–984

CGIAR (2000) CGIAR research priorities for marginal lands. Consultative group on International Agricultural Research 339

Chakraborty S, Newton AC (2011) Climate change, plant diseases and food security: an overview. Plant Pathol 60(1):2–14. https://doi.org/10.1111/j.1365-3059.2010.02411.x

Chivenge P, Mabhaudhi T, Modi AT, Mafongoya P (2015) The potential role of neglected and underutilised crop species as future crops under water scarce conditions in sub-Saharan Africa. Int J Environ Res Public Health 12(6):5685–5711. https://doi.org/10.3390/ijerph120605685

Choukr-allah R, Nanduri KR, Hirich A, Shahid M, Alshankiti A, Toderich K, Gill S, Butt KUR (2016) Quinoa for marginal environments: towards future food and nutritional security in MENA and Central Asia regions. Front Plant Sci 7(346):1–11. https://doi.org/10.3389/fpls.2016.00346

Conde C, Liverman D, Flores M, Ferrer R, Araújo R, Betancourt E, Villareal G, Gay C (1997) Vulnerability of maize crops in Mexico to climate change. Clim Res. 9:17–23

Craufurd P, Bojang M, Wheeler T, Summerfield R (1998) Heat tolerance in cowpea: effect of timing and duration of heat stress. Ann Appl Biol 133(2):257–267

De Ron AM, Sparvoli F, Pueyo JJ, Bazile D (2017) Editorial: protein crops: food and feed for the future. Front Plant Sci 8:105. https://doi.org/10.3389/fpls.2017.00105

Duwayri MA (2001) Alternative crops and cultivars for new opportunities. Crop diversification in The Asia-Pacific Region. FAO, Rome, p 168

Eganathan P, Subramanian HS, Latha R, Rao CS (2006) Oil analysis in seeds of Salicornia brachiata. Ind Crop Prod 23(2):177–179

Eisa S, Hussin S, Geissler N, Koyro HW (2012) Effect of NaCl salinity on water relations, photosynthesis and chemical composition of quinoa (*Chenopodium quinoa* Willd.) as a potential cash crop halophyte. Aust J Crop Sci 6(2):357–368

FAO (2009) How to feed the World in 2050. In: Nations FaAOotU (ed) . High-Level Expert Forum, Rome

FAO (2011) The state of the world's land and water resources for food and agriculture. Food and Agriculture Organization of the United Nations, Rome

FAO, IFAD, WFP (2015) The state of food insecurity in the world. Food and Agriculture Organization of the United Nations (FAO), Rome, p 62

Fghire R, Wahbi S, Anaya F, Issa Ali O, Benlhabib O, Ragab R (2015) Response of Quinoa to different water management strategies: field experiments and Saltmed model application results. Irrig Drain 64(1):29–40. https://doi.org/10.1002/ird.1895

Filali K, Hirich A, Ouafae B, Redouane C-A, Ragab R (2017) Yield and dry matter simulation using the Saltmed model for five Quinoa (Chenopodium Quinoa) accessions under deficit irrigation in South Morocco. Irrig Drain 66:340. https://doi.org/10.1002/ird.2116

Frison EA, Cherfas J, Hodgkin T (2011) Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. Sustainability 3(1):238–253

Geerts S, Raes D, Garcia M, Vacher J, Mamani R, Mendoza J, Huanca R, Morales B, Miranda R, Cusicanqui J, Taboada C (2008) Introducing deficit irrigation to stabilize yields of quinoa (*Chenopodium quinoa* Willd.). Eur J Agron 28(3):427–436

Geerts S, Raes D, Garcia M, Taboada C, Miranda R, Cusicanqui J, Mhizha T, Vacher J (2009) Modeling the potential for closing quinoa yield gaps under varying water availability in the Bolivian Altiplano. Agric Water Manag 96(11):1652–1658. https://doi.org/10.1016/j.agwat.2009.06.020

Giwa S, Abdullah LC, Adam NM (2010) Investigating "Egusi" (Citrullus colocynthis L.) seed oil as potential biodiesel feedstock. Energies 3(4):607–618

Glenn EP, O'Leary JW, Watson MC, Thompson TL, Kuehl RO (1991) Salicornia bigelovii Torr.: an oilseed halophyte for seawater irrigation. Science 251(4997):1065–1068

Glenn EP, Coates WE, Riley JJ, Kuehl RO, Swingle RS (1992) Salicornia bigelovii Torr.: a seawater-irrigated forage for goats. Anim Feed Sci Technol 40(1):21–30

Greenway H, Munns R (1980) Mechanisms of salt tolerance in nonhalophytes. Annu Rev Plant Physiol 31(1):149–190

Hendricks RC (2008) Potential carbon negative commercial aviation through land management. 12th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery. NASA Glenn Research Center. February 17–22, 2008. Honolulu, HI; United States

Hirich A (2013) Using deficit irrigation with treated wastewater to improve crop water productivity of sweet corn, chickpea, faba bean and quinoa. Revue Marocaine des Sciences Agronomiques et Vétérinaires 2(1):15–22

Hirich A, Choukr-Allah R (2013) Faba bean (Vicia faba L.) production under deficit irrigation with treated wastewater applied during vegetative stage. Desalin Water Treat 52(10–12):2214–2219. https://doi.org/10.1080/19443994.2013.804452

Hirich A, Choukr-Allah R, Jacobsen S-E, El Yousfi L, El Omari H (2012) Using deficit irrigation with treated wastewater in the production of quinoa (*Chenopodium quinoa* Willd.) in Morocco. Revista Científica UDO Agrícola 12(3):570–583

Hirich A, Choukr-Allah R, Jacobsen S-E (2013) The combined effect of deficit irrigation by treated wastewater and organic amendment on quinoa (Chenopodium quinoa Willd.) productivity. Desalin Water Treat 52(10–12):2208–2213. https://doi.org/10.1080/19443994.2013.777944

Hirich A, Choukr-Allah R, Jacobsen SE (2014a) Deficit irrigation and organic compost improve growth and yield of Quinoa and pea. J Agron Crop Sci 200:390–398. https://doi.org/10.1111/jac.12073

Hirich A, Choukr-Allah R, Jelloul A, Jacobsen S-E (2014b) Quinoa (Chenopodium quinoa Willd.) seedling, water uptake and yield responses to irrigation water salinity. Acta Hortic 1054:145–152

Hirich A, Jelloul A, Choukr-Allah R, Jacobsen SE (2014c) Saline water irrigation of quinoa and chickpea: seedling rate, stomatal conductance and yield responses. J Agron Crop Sci 200:378–389. https://doi.org/10.1111/jac.12072

Hirich A, Ragab R, Choukr-Allah R, Rami A (2014d) The effect of deficit irrigation with treated wastewater on sweet corn: experimental and modelling study using SALTMED model. Irrig Sci 32(3):205–219. https://doi.org/10.1007/s00271-013-0422-0

Hirich A, Fatnassi H, Ragab R, Choukr-Allah R (2016) Prediction of climate change impact on corn grown in the south of Morocco using the Saltmed model. Irrig Drain 65(1):9–18. https://doi.org/10.1002/ird.2002

Hussain MI, Lyra D-A, Farooq M, Nikoloudakis N, Khalid N (2016) Salt and drought stresses in safflower: a review. Agron Sustain Dev 36(1):4

IPCC IPoCC (2014) Climate change 2014–impacts, adaptation and vulnerability: regional aspects. Cambridge University Press, Cambridge

Isleib J (2012) Exploring alternative field crops. Michigan State University Extension, East Lansing, MI

Jacobsen S-E, Quispe H, Mujica A (2000) Quinoa: an alternative crop for saline soils in the Andes. CIP Program Report

Jacobsen SE, Monteros C, Christiansen JL, Bravo LA, Corcuera LJ, Mujica A (2005) Plant responses of quinoa (*Chenopodium quinoa* Willd.) to frost at various phenological stages. Eur J Agron 22(2):131–139. https://doi.org/10.1016/j.eja.2004.01.003

Jacobsen SE, Monteros C, Corcuera LJ, Bravo LA, Christiansen JL, Mujica A (2007) Frost resistance mechanisms in quinoa (*Chenopodium quinoa* Willd.). Eur J Agron 26(4):471–475. https://doi.org/10.1016/j.eja.2007.01.006

Jaradat A, Shahid M (2006) Patterns of phenotypic variation in a germplasm collection of Carthamus tinctorius L. from the Middle East. Genet Resour Crop Evol 53(2):225–244

Jaradat AA, Shahid M (2012) The dwarf saltwort (Salicornia bigelovii Torr.): evaluation of breeding populations. ISRN Agronomy 2012:1–10

Jones PG, Thornton PK (2003) The potential impacts of climate change on maize production in Africa and Latin America in 2055. Glob Environ Chang, 13(1):51–59

Jones PD, Lister DH, Jaggard KW, Pidgeon JD (2003) Future climate impact on the productivity of sugar beet (Beta vulgaris L.) in Europe. Clim Chang 58(1–2), 93–108

Kang Y, Khan S, Ma X (2009) Climate change impacts on crop yield, crop water productivity and food security – a review. Prog Nat Sci 19(12):1665–1674. https://doi.org/10.1016/j.pnsc.2009.08.001

Khalili M, Alireza P-A, Naghavi MR, Mohammad-Amini E (2014) Evaluation of drought tolerance in safflower genotypes based on drought tolerance indices. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 42(1):214

Knox J, Hess T, Daccache A, Wheeler T (2012) Climate change impacts on crop productivity in Africa and South Asia. Environ Res Lett 7(3):034032

Koyro H-W, Eisa S (2008) Effect of salinity on composition, viability and germination of seeds of *Chenopodium quinoa* Willd. Plant Soil 302(1):79–90. https://doi.org/10.1007/s11104-007-9457-4

Koyro H-W, Lieth H, Eisa SS (2008) Salt tolerance of *Chenopodium quinoa* Willd., grains of the Andes: influence of salinity on biomass production, yield, composition of reserves in the seeds, water and solute relations mangroves and halophytes: restoration and utilisation. In: Lieth H, Sucre MG, Herzog B (eds) Tasks for vegetation science 34, vol 43. Springer, Netherlands, pp 133–145. https://doi.org/10.1007/978-1-4020-6720-4_13

Lavini A, Pulvento C, d'Andria R, Riccardi M, Choukr-Allah R, Belhabib O, İncekaya Ç, Metin Sezen S, Qadir M, Jacobsen SE (2014) Quinoa's potential in the Mediterranean region. J Agron Crop Sci 200(5):344–360. https://doi.org/10.1111/jac.12069

Ludwig F, Asseng S (2006) Climate change impacts on wheat production in a Mediterranean environment in Western Australia. Agric Syst 90(1–3):159–179

Maes WH, Achten WM, Reubens B, Raes D, Samson R, Muys B (2009) Plant–water relationships and growth strategies of Jatropha curcas L. seedlings under different levels of drought stress. J Arid Environ 73(10):877–884

Matthews RB, Kropff M J, Horie T, Bachelet D (1997) Simulating the impact of climate change on rice production in Asia and evaluating options for adaptation. Agric Syst 54(3):399–425

Mathews C, Saxena K (2005) Prospects for pigeonpea cultivation in drought-prone areas of South Africa. In: Proceedings of the First International Edible Legume Conference in conjunction with the 4th World Cowpea Congress, Durban, South Africa. 17–21 April 2005. ICRISAT,

Mazhar M, Arif A, Chriyaa A, El Mzouri L, Derkaoui M (2000) Cactus protects soil and livestock in Rhamna Region. In: IV International Congress on Cactus Pear and Cochineal 581. pp 329–332

Nefzaoui A, Ben Salem H (2001) Opuntia: A strategic fodder and efficient tool to combat desertification in the WANA region. In: Mondragon JC, Perez GS (eds) Cactus (Opuntia spp.) as forage. FAO, Rome, pp 73–89

Patel S (2016) Salicornia: evaluating the halophytic extremophile as a food and a pharmaceutical candidate. 3. Biotech 6(1):104. https://doi.org/10.1007/s13205-016-0418-6

Patel P, Hall A (1990) Genotypic variation and classification of cowpea for reproductive responses to high temperature under long photoperiods. Crop Sci 30(3):614–621

Rao N, Shahid M (2011) Potential of cowpea [Vigna unguiculata (L.) Walp.] and guar [Cyamopsis tetragonoloba (L.) Taub.] as alternative forage legumes for the United Arab Emirates. Emirates Journal of Food and Agriculture 23(2):147

Rao N, Shahid M (2012) Quinoa–a promising new crop for the Arabian peninsula. American-Eurasian J Agric Environ Sci 12:1350–1355

Rao NK, Shahid M, Shabbir AS (2009) Alternative crops for diversifying production systems in the Arabian peninsula. Arab Gulf J Scientific Res 27(4):195–203

Rao NK, McCann I, Shahid SA, Butt KUR, Al Araj B, Ismail S (2017) Sustainable use of salt-degraded and abandoned farms for forage production using halophytic grasses. Crop Pasture Sci 68(5):483–492

Rasheed M JZ, Ahmad K, Ashraf M, Al-Qurainy, F, Khan S, Athar HUR (2015) Screening of diverse local germplasm of guar [Cyamopsis tetragonoloba (L.) Taub.] for salt tolerance: a possible approach to utilize salt-affected soils. Pak J Bot, 47(5):1721–1726

Rauf S, Al-Khayri JM, Zaharieva M, Monneveux P, Khalil F (2016) Breeding strategies to enhance drought tolerance in crops. In: Advances in plant breeding strategies: agronomic. Springer, Abiotic and Biotic Stress Traits, pp 397–445

Ray D, Livingston M (1986) Response of guar to drought conditions. Forage and grain: a college of agriculture report, series P-67:125–126

Razzaghi F, Ahmadi SH, Jacobsen SE, Jensen CR, Andersen MN (2012) Effects of salinity and soil–drying on radiation use efficiency, water productivity and yield of quinoa (*Chenopodium quinoa* Willd.). J Agron Crop Sci 198(3):173–184. https://doi.org/10.1111/j.1439-037X.2011.00496.x

Rodríguez-Medina M, la Lanza-Espino D, Hernández-Pulido S (1998) Decomposition of Salicornia subterminalis in Caimanero lagoon, Mexico. Cienc Mar 24(2):241

Rosenzweig C, Phillips J, Goldberg R, Carroll J, Hodges T (1996) Potential impacts of climate change on citrus and potato production in the US. Agric Syst 52(4):455–479

Rueda-Puente E, García-Hernández J, Preciado-Rangel P, Murillo-Amador B, Tarazón-Herrera M, Flores-Hernández A, Holguin-Peña J, Aybar A, Barrón Hoyos J, Weimers D (2007) Germination of Salicornia bigelovii ecotypes under stressing conditions of temperature and salinity and ameliorative effects of plant growth-promoting bacteria. J Agron Crop Sci 193(3):167–176

Sapeta H, Costa JM, Lourenco T, Maroco J, Van der Linde P, Oliveira MM (2013) Drought stress response in Jatropha curcas: growth and physiology. Environ Exp Bot 85:76–84

Sauer PA, Sullivan P (2000) Alternative agronomic crops. Agronomy Series (ATTRA) December 2000:12

Selim MY (2009) Reducing the viscosity of Jojoba methyl Ester diesel fuel and effects on diesel engine performance and roughness. Energy Convers Manag 50(7):1781–1788

Shabala S, Hariadi Y, Jacobsen SE (2013) Genotypic difference in salinity tolerance in quinoa is determined by differential control of xylem Na(+) loading and stomatal density. J Plant Physiol 170(10):906–914. https://doi.org/10.1016/j.jplph.2013.01.014

Shahid M, Rao N (2014) Diversity of Citrullus colocynthis (L.) Schrad. (Cucurbitaceae) in the United Arab Emirates. J New Biol Rep 3(2):145–150

Shahid M, Jaradat AA, Rao NK (2013) Use of marginal water for Salicornia bigelovii Torr. Planting in the United Arab Emirates. In: Developments in soil salinity assessment and reclamation. Springer, Heidelberg, pp 451–462

Sharma P, Sardana V, Banga S (2013) Salt tolerance of Indian mustard (Brassica juncea) at germination and early seedling growth. Environ Exp Biol 11:39–46

Shipton P (1977) Monoculture and soilborne plant pathogens. Annu Rev Phytopathol 15 (1):387–407

Singh B, Ajeigbe H, Tarawali SA, Fernandez-Rivera S, Abubakar M (2003) Improving the production and utilization of cowpea as food and fodder. Field Crop Res 84(1):169–177

Thompson S, Hauser RJ, Guither HD, Nafziger ED (1993) Evaluating alternative crops from a marketing perspective: the case of canola. J Prod Agric 6(4):575–584

Toader M, Roman GV, Ionescu A-M (2011) Chemical composition and nutritional values of some alternative crops promoted in organic agriculture. UASVM Bucharest, Series A LIV 2011:293–296

Trnka M, Dubrovský M, Žalud Z (2004) Climate change impacts and adaptation strategies in spring barley production in the Czech Republic. Clim Chang 64(1–2):227–255

Undersander DJ, Putnam DH, Kaminski AR, Kelling KA, Doll JD, Oplinger ES, Gunsolus JL (1991) Guar. Alternative field crop manual. University of Wisconsin cooperative extension service, University of Minnesota extension service. Cent Altern Plant Anim Prod. http://www.hort.purdue.edu/newcrop/afcm/cowpea.html

ur Rahman H, Malik SA, Saleem M (2004) Heat tolerance of upland cotton during the fruiting stage evaluated using cellular membrane thermostability. Field Crop Res 85(2):149–158

Ventura Y, Sagi M (2013) Halophyte crop cultivation: the case for Salicornia and Sarcocornia. Environ Exp Bot 92:144–153. https://doi.org/10.1016/j.envexpbot.2012.07.010

Verma D, Rana BS, Kumar R, Sibi M, Sinha AK (2015) Diesel and aviation kerosene with desired aromatics from hydroprocessing of jatropha oil over hydrogenation catalysts supported on hierarchical mesoporous SAPO-11. Appl Catal A Gen 490:108–116

Wahid A, Gelani S, Ashraf M, Foolad MR (2007) Heat tolerance in plants: an overview. Environ Exp Bot 61(3):199–223

Wiebe K, Croppenstedt A, Raney T, Skoet J, Zurek M, Tschirley J, Cluff M (2008) The state of food and agriculture 2008. Biofuels: Prospects, risks and opportunities. Food and Agriculture Organization of the United Nations, Rome, Italy

Win KT, Oo AZ (2015) Genotypic difference in salinity tolerance during early vegetative growth of cowpea (Vigna unguiculata L. Walp.) from Myanmar. Biocatal Agric Biotechnol 4(4):449–455

Winkel T, Lhomme JP, Laura JPN, Alcón CM, del Castillo C, Rocheteau A (2009) Assessing the protective effect of vertically heterogeneous canopies against radiative frost: the case of quinoa on the Andean Altiplano. Agric For Meteorol 149(10):1759–1768. https://doi.org/10.1016/j.agrformet.2009.06.005

Wolfe MS (2000) Crop strength through diversity. Nature 406(6797):681–682

Yazar A, Incekaya Ç, Sezen SM, Jacobsen S-E (2015) Saline water irrigation of quinoa (Chenopodium quinoa) under Mediterranean conditions. Crop Pasture Sci 66(10):993–1002

Chapter 2
Grain Legumes May Enhance High-Quality Food Production in Europe

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Abstract At present high-quality protein-rich food sources are increasing to offer a sustainable alternative for the growing world population demand. Plant protein production favors biodiversity, environmental sustainability, and human health.

The production of plant proteins is more cost-effective and resource-efficient compared to meat proteins since they are less exigent in terms of natural resources (nitrogen, water, etc.). The natural nitrogen fixation of legumes enriches soils and benefits cropping systems. Reducing red meat consumption and increasing consumption of protein from other sources could also increase health benefits.

In this chapter we analyze the production and use of protein crops for human consumption and review their sustainability under Northern and Southern European environments.

Keywords Agricultural systems · Climate change · Sustainability · Protein crops

2.1 Introduction

2.1.1 Role of Protein Crop in Europe

It is predicted that the world population will reach 9 billion by 2050 (United Nations 2017), from 7.5 billion today; by then the middle class will be joined by 3 billion

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people (Kharas 2010) leading to a huge increase demand of protein food with high quality (FAO 2011).

Europeans face a dual challenge: to produce larger quantities of high-quality protein-rich food sources in response to an increasing global demand, taking into account at the same time human health, sustainability of agricultural practices, and biodiversity. However, there are currently few options to encourage this. Vegetable protein sources should have high protein content, high digestibility, low antinutritional factor levels, high amount of essential amino acids, and a comparable price to animal protein sources (De Visser 2013). These challenges are possible by developing protein food from high-quality (grain legumes) protein crops, using optimized, sustainable production and processing methods.

All protein crops (plants naturally rich in proteins) present multiple interests in economic, agronomic, and environmental terms. High-quality protein crops like amaranth and quinoa are considered climate-proof crops (Jacobsen 2014) that cope with climate changes thanks to their tolerance to abiotic stresses (Adolf et al. 2013; Jacobsen et al. 2003; Lavini et al. 2016, 2014; Pulvento et al. 2015; Riccardi et al. 2014). The natural nitrogen fixation in legumes allows the production of vegetable proteins; the enrichment of the soils in nitrogen and organic matter; reduction of weeds, pests, and diseases in the agricultural systems; and improvements to the wider environment through greenhouse gas sequestration. After these advantages, the EU legume production fell (Bues et al. 2013).

The arable land (Fig. 2.1) for dry pulses in the EU-28 during last 10 years, ranged from 1.5 to 2.1 million hectares. In recent times this area increased considerably. Between 2013 and 2015, an increase of 64.7% at EU level was recorded (Eurostat 2016). These changes respond to attractive prices for farmers in relation to wheat, as well as the increase of costs of imported soybeans and synthetic fertilizers since the year 2000 (Anglade et al. 2015).

Other reasons are related to the greening measures provided by common agricul tural policy (CAP); green direct payment schemes for nitrogen-fixing crops (such as dry pulses) were introduced by CAP. In addition, in 2015, 16 EU countries started supporting the protein crops with 11% of the voluntary coupled support framework fixed by the Commission. For this reason, farmers increased sowing areas with dry pulses.

The consumption of protein crops has been significantly reduced, especially for human consumption, following the change in eating habits with a marked preference to consume protein foods of animal origin. The gradual reduction of the grain legume production area responds to agronomic, economic, and social reasons. Factors such as simplified cropping systems targeted toward cereal monoculture with few productive varieties, suitable for mechanization and defined grain quality, pushed consumers toward reduced protein sources (Zaccardelli et al. 2010).

Grain legumes, excluding soybeans, are present throughout the world, where they occupy an area of about 70 million hectares, virtually unchanged in the last decade. The production reached more than 60 million tonnes, with improvements in yields that ranged 0.8–1 t ha^{-1} registered in the last decade (Zaccardelli et al. 2010).

Today, the European Union imports soya bean food to meet the current 70% deficit in protein crop production (Bues et al. 2013).

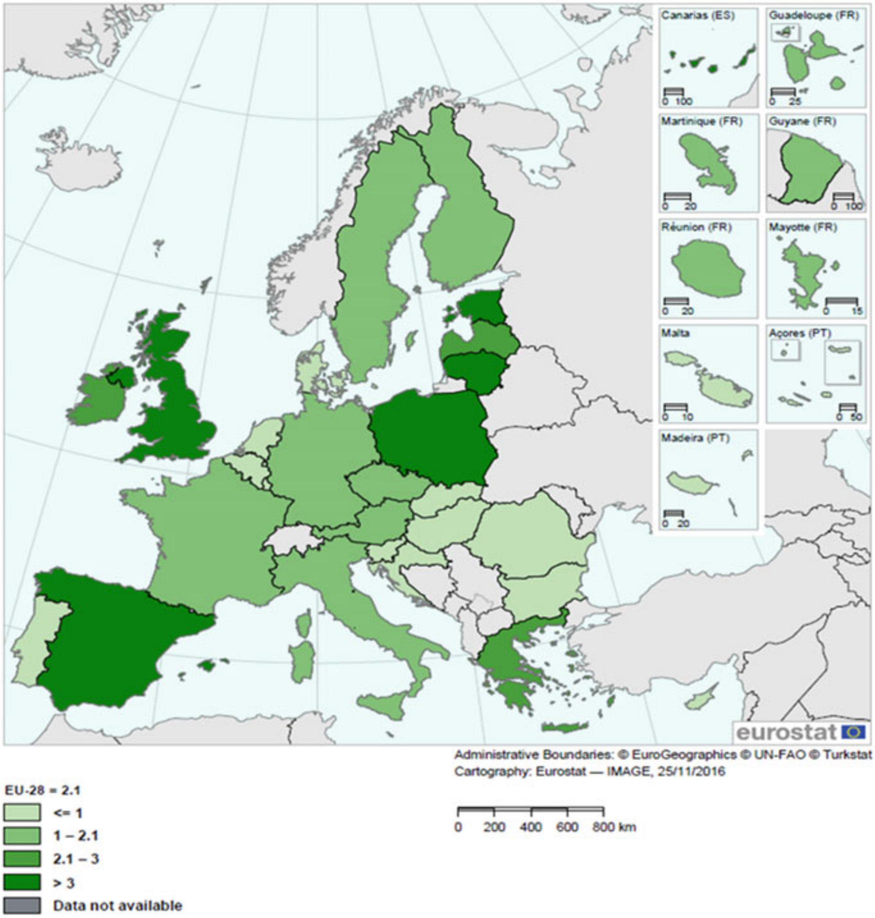

Fig. 2.1 Share of dry pulses in EU total arable land 2015 (%). Source: Eurostat (http://ec.europa.eu/eurostat/statistics-explained/index.php/Dry_pulses_in_EU_agriculture_-_statistics_on_cultivation,_production_and_economic_value)

Dry pulses belong to leguminous family and produce dry seeds that can vary in shapes, sizes, and colors; these crops are fundamental because of their high level of proteins and for the benefits they offer to improve the soil, cropping systems, and the environment. Dry pulse proteins can feed both animals and humans.

Worldwide abiotic stress reduces more than 50% of crop yields (Rodziewicz et al. 2014). The Mediterranean Europe is characterized by marginal areas affected by severe drought and salinity conditions; Ozturk et al. (2015) predicted that air temperatures and heavy rains would rise by 2100 in this area. Pulses can grow in arid climates under limited, and often erratic, rainfall; several studies showed that chickpea and lentil are as drought-resistant (Toker and Yadav 2010). Among legumes, there is a wide variation of yield response to dry environmental conditions, offering opportunities for more resilient cropping systems for a changing climate (Daryanto et al. 2015).

The year 2016 was declared by UN as the International Year of Pulses. The FAO view was to spread the beneficial characteristics of pulses for the human nutrition and for the environment. The FAO focused on 11 primary pulses adapted to different pedo-climatic conditions and cropping systems.

This review includes recent information on grain legumes from the PROTEIN2FOOD project financed by the EU Horizon 2020 research and innovation framework program. PROTEIN2FOOD aims to develop innovative, cost-effective and resource-efficient, locally produced, healthy plant proteins for human consumption, with a positive impact on bio-economy, environment, biodiversity, human health, food security, and social innovation (http://www.protein2food.eu).

We present an overview grain legume crops for human consumption and review the production and impacts under European conditions.

2.2 Legumes in Northern Europe

2.2.1 Grain Legume Production in the Nordic Region of Europe

In this chapter we consider Finland, Sweden, Norway, and Denmark as Northern Europe; therefore the description of legume production primarily addresses these countries. The climate in this region is characterized by long cold winters with short days and short summers with long days. Frosts during late spring and early autumn and the solar radiation availability are factors that limit the growing season length. Compared to the rest of Europe, the range of crops is reduced, so legume species produced are mainly pea and faba bean (Maracchi et al. 2005; Stoddard 2013).

2.2.2 History of Grain Legume Production

Northern Europe has a rich history of legume consumption and production. Human consumption of fava beans and peas has been documented in Northern Europe as far back as the Viking Age (700–1050). Both were important sources of protein and food that could be stored for long periods, ensuring food to families during the Nordic winters. During the sixteenth century, beans and peas started to be harvested green for fresh consumption, but the uses for beans and peas in this period were mostly as flour for bread and soup (Vikinge Center 2017).

The major introduction of legumes into the European cropping systems took place in 1750–1880, a period considered as an Agricultural Revolution for the continent as a whole (Chorley 1981). By then, legumes were the only sources of nitrogen. Between 1940 and the end of 1970, production systems changed with an exponential increase in the use of synthetic fertilizers. In this period, developed countries considered fertilizers as an effective and inexpensive option to produce food for an increasing population (Vitousek et al. 1997). These fertilizers also reduced the need for legume cultivation, allowing farmers to focus on other crops. In general for Northern Europe, legumes covered a low percentage of the agricultural area (e.g., 0.1% of the area covered in Denmark in 1965). Most countries in the region experienced rising production after 1975 due to EU subsidization and a reduction in the 1990s due to increased soybean imports (Stoddard 2013; Cernay et al. 2015), based on a change in the EU policy not supporting internal protein production.

A shift in societal opinion is occurring throughout Europe that favors sustainable agriculture and organic production (Siddique et al. 2012). This shift has been accompanied by increases in production of legumes in Northern Europe since 2010 (Stoddard 2013). Strong social pressure favor the increased domestic production of grain legumes to reduce dependency on GM soy imports from South America and to reduce negative effects of cereal production on the environment (Cernay et al. 2015). In addition there is a trend toward reduced meat production and consumption, which require the search for vegetable protein sources. The market for non-GM plant proteins for human food products is a promising "stepping stone" for development of legume breeding programs and value chains throughout Europe (Schreuder and de Visser 2014).

2.2.3 Legumes in the Nordic Diet

Nowadays legume consumption in the Nordic countries has decreased along with the increased production and access of meat in the diets. Despite the long-standing tradition of legume consumption in Scandinavia, pulses today contribute with only 1% to the daily protein intake. Peas are the most consumed legume in all four countries (Kammlade et al. 2017).

The consumption of animal protein has increased with time in the Nordic countries, following the global trend for developed countries (Fig. 2.2). By 2009, more than 60% of protein in the average daily diet in the Nordic countries came from animal products, about 20% from grains, and the rest from vegetables, roots, oils, fruits, and miscellaneous (Fig. 2.2) (Kammlade et al. 2017).

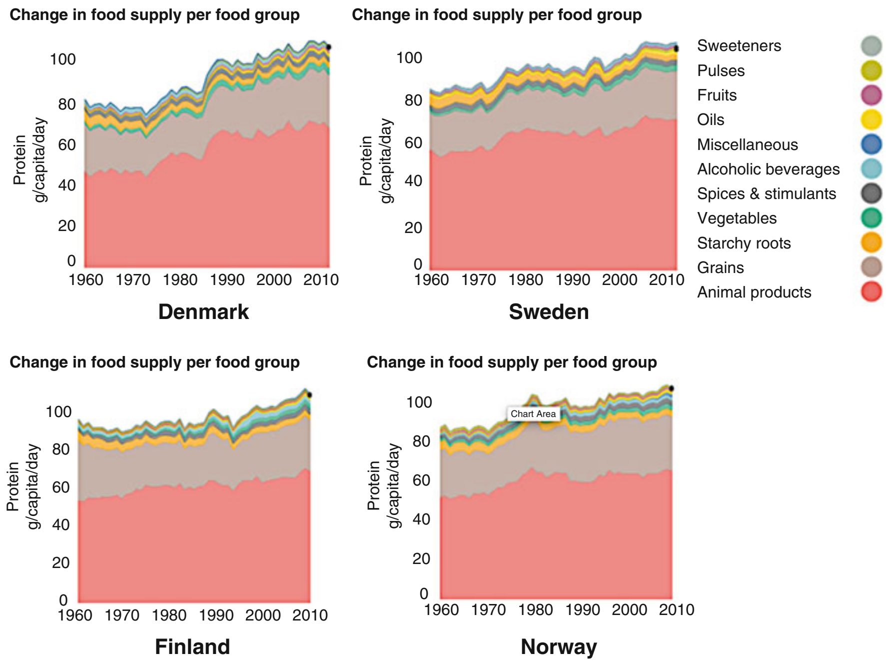

Fig. 2.2 Development of the protein food supply in Northern European diets from 1960–2010 (Kammlade et al. 2017)

The largest meat producer in Europe and the world's biggest pork exporter (Danish Crown AmbA) is Danish (Chemnitz and Becheva 2014). High meat diets and meat production involve a large demand for protein feed ingredients, which require large areas of arable land (both within the region and abroad). In 2013, 80% of the crop production in Denmark was dedicated to animal feed (Danish Agriculture and Food Council 2014). The demand for protein feed ingredients in the EU was 23 million t (2003–2007), and approximately 75% of it was imported soybean meal (GL-Pro 2005; LMC International 2009).

Replacing feed crops with crops for direct human consumption is a potential a key factor to ensure food security in the future (Foley et al. 2011).

In the context of food security, it is relevant to consider the nutritional value of the crops, to make sure that the crops grown can supply high-quality and high-value food products.

		Wheat	Pea	Faba bean	Common vetch*	Bitter vetch*	Chickpea Desi*	Blue lupin	White lupin	Yellow lupin**	Soyabean seed
Components (% dry matter)	Proteins	12	24	29	28	26	22	34	38	42	39
	Starch	69	51	43	43	nd	41	0	0	0	0
	Fats	1.7	1.1	1.7	1.6	1.1	6.1	5.9	9.5	6.1	20
	Ash	1.8	3.5	4	4	3.3	3.2	3.8	3.9	3.8	5.9
	Crude fibres	2.5	6	9.3	4.5	4.1	10	16	13	18	5.9
Amino acids (% protein)	Lysine	2.9	7.3	6.5	5.7	6.4	6.8	5	4.9	5.3	6.2
	Methionine + cysteine	4	2.3	2	1.8	2.4	2	2.6	2.4	2.9	3.1
	Threonine	3.1	3.8	3.6	3.3	3.8	3.4	3.9	3.7	3.5	4
	Tryptophane	1.2	0.9	0.8	nd	nd	0.8	0.7	0.7	0.8	1.3

Sources: INRA, France (2002); *Io7 Banque de données de l'alimentation animale - AFZ, France (2001); **GRDC, Australia (1997); nd = no data available.

Fig. 2.3 Selected nutritional content of wheat and different legume crops (GL-Pro 2005)

2.2.4 *Nutritional Benefits*

Legumes are valuable elements for a healthy diet due to their high protein levels (Crépon et al. 2010; Tharanathan and Mahadevamma 2003). The proteins from legumes are combined with a high amount of dietary fibers, which are not present in meat. Several studies have claimed the benefit of legumes for different physiological processes controlling metabolic diseases. Legumes are attracting attention for their therapeutic advantages for people suffering from metabolic disorders (Prins and Nuijten 2015; Shehata et al. 1988; Simpson et al. 1981).

Legumes have higher nutritional quality compared to cereals with doubled protein content, more fiber and less starch (Fig. 2.3).

Legumes can also be competitive to meat. Faba bean has higher amount of protein (27% vs 19%) and less fat (2% vs 6%) than chicken meat (DTU Fødevareinstituttet 2017). Legumes represent a healthy and environmentally sound alternative to animal protein consumption.

2.2.5 *Trends and Opportunities for Legume Production in Northern Europe*

Current trends in Northern Europe, particularly in Sweden and Germany, show an increasing interest in fava bean as a profitable crop. In Sweden, from 2001 to 2015, the cultivated area with fava beans increased by 150% (to 25,000 ha) with yields ranging 3–4 t/ha (Nätterlund 2015). Researchers are experimenting with fresh fava beans of the Gloria variety (Nielsen 2016). The area cultivated with soy bean in nearby countries such as Germany has doubled between 2003 and 2015, yet still at a low level (Wilbois 2015). The production of many of the other grain legumes such as lupin, field pea, and fava bean has recently started to increase at a very rapid rate; from 2013 to 2015, the production area doubled from 74,700 ha to 160,600 ha (Wilbois 2015).

Recent data (Eurostat 2017) in Fig. 2.4 show an increasing cultivation area of fava beans in Denmark, Sweden, and Finland (no available data for Norway). Currently the highest legume production is in Sweden with fava beans and peas as the major legumes produced (Table 2.1). Only Denmark had a noticeable production of lupins up to 700 ha in 2010–2012.

The profits for fava beans have the potential to exceed those of organic lucerne (651 Euro/ha), oats (757 Euro/ha), and spring barley (603 Euro/ha) and compete with winter wheat (898 Euro/ha) (Farmatonline 2016).

The price of 0.4 Euro/kg for organic fava beans gives the opportunity to introduce in the market a cheap and competitive product, also for bulk purchase (Table 2.2).

Farmers rely on crops that pay off financially and are competitive compared to other possibilities. Legume on-farm value is not only related to their specific contribution margin but also to the additional ecological services providing indirect value. A survey from 2000 showed that 60% of farmers indicated that the main reason to grow grain legumes was the rotational purposes and soil improvement (Köpke and Nemecek 2010).

These simplified numbers do not represent the complex nature of accounting for the precise value on farm which could include site- and time-dependent variations, potential replacement of N costs for the following crop, replacement of imported fodder costs if used as feed, potentially lost or gained subsidies, etc. If the production system includes winter fava bean, a greater contribution margin could be obtained with the yields as high as 5.7 t/ha.

2.2.6 Challenges and Opportunities

2.2.6.1 Challenge 1: Breeding

By 2014, global cultivation area of pulse crops constituted approximately 10$^{\%}$ of the area with cereal crops, with a rate of growth of 0.4% per year since mid-1990s. Yields for cereals have increased 1.5% annually, whereas yields for pulses have only an annual increase of 0.4% (Schreuder and de Visser 2014). In most of the countries in the Nordic region, breeding programs are absent or discontinuous along the twentieth century, but efforts are taken the first decade of the twenty-first century

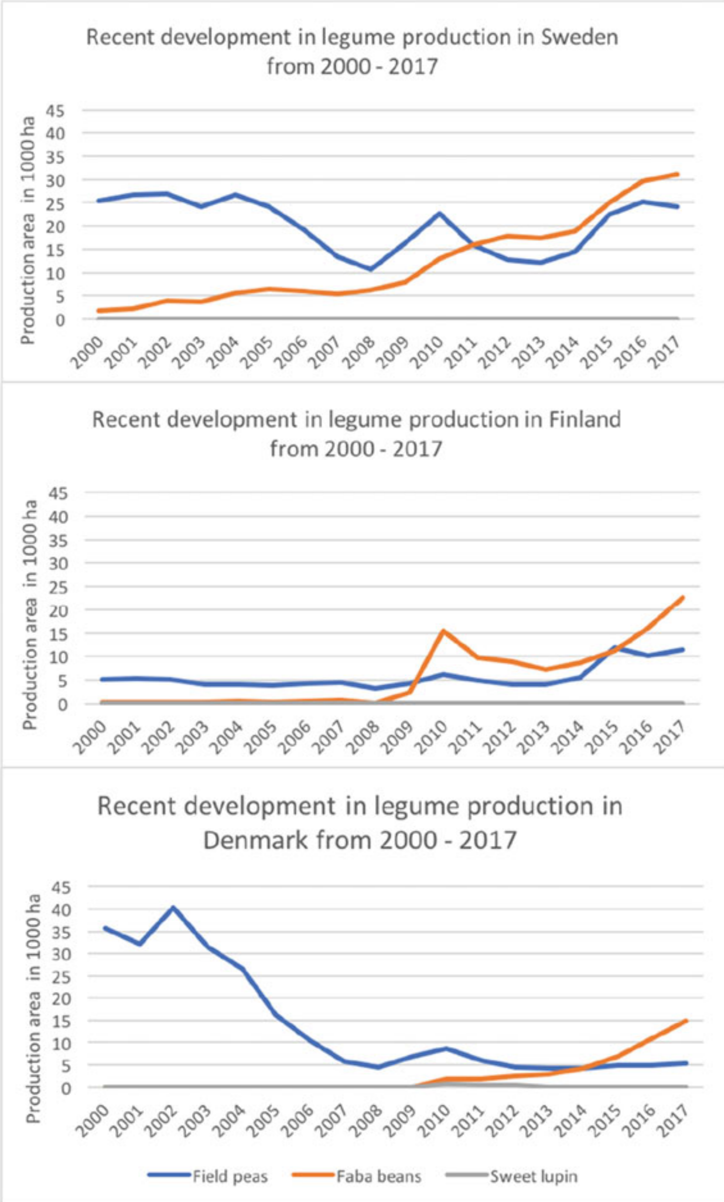

Fig. 2.4 Recent legume production area development in Sweden, Finland and Denmark from 2000-2017 (Eurostat 2017)

(Stoddard 2013). In order to increase legume production in the Scandinavian region, plant breeders could focus on the following aspects:

Yield Stability Yields of legumes are highly variable in Europe when compared to other continents (e.g., America) and other crops. In Northern Europe lupin, bean,

Table 2.1 Area cultivated with legumes in Northern Europe in 2017 (Source: Eurostat 2017)

	Faba beans	Peas
Sweden	31,130 ha	24,060 ha
Finland	22,600 ha	11,400 ha
Denmark	14,800 ha	5,300 ha

Table 2.2 Profit estimates for Danish legume production for 2017

Crop	Yield (t/ha)	Price (Euro)	Inputs (Euro)	Total profit (Euro/ ha)
Organic fava beans	3.7	0.4	614	818
Conventional fava beans	4.6	0.2	4,426,596	−101
Organic lupin	2	0.4	742	260
Conventional lupin	No production			
Organic feed peas	4	0.2	717	261
Conventional feed peas	5.4	0.2	422	94
Conventional winter wheat	9.6	0.1	862	396
Conventional winter raps	4.5	0.4	735	339

Source: SEGES (farmonline) with averages for 1 year where 1 Euro = 7.43 DKK (11/2016–11/2017) from European Central Bank Eurosystem (2017)

vetch, fava bean, and pea are all more variable than rapeseed, potato, oat, barley, and wheat (Cernay et al. 2015). The suitability of the species according to the soil type has great influence in the yields in the Nordic region (Stoddard 2013). White lupin has a potential for autumn sowing, but it has a narrow soil adaptation, whereas both pea and fava bean have wide climatic and soil adaptability, with a high potential for yield increase via autumn sowing (Schreuder and de Visser 2014).

Availability of improved technologies and agricultural practices in the region constitute opportunities to produce food legumes with more stable yields (Siddique et al. 2012). Promising results were seen in recent trials with winter fava beans; yields doubled (4.7–5.7 t/ha) when sown in October compared to spring sowing in April (1.2–2.3 t/ha) (Jacobsen 2016a).

Tolerance to Abiotic and Biotic Conditions Early maturity, especially for fava bean, is important in the Nordic region to reduce risk of harvest difficulties from a wet autumn. Harvesting green fava beans to consume them as fresh could represent an alternative to shorten the cycle as it has been tried in Sweden (Nielsen 2016). Agricultural practices such as intercropping would also help to reduce the competition with weeds (Kontturi et al. 2011). Tolerance to low temperatures is also important to cope with cold winters and prolonged snow cover. Tolerance to pests (aphids) and diseases (such as gray mold in lupin; brown rust and chocolate spot in fava beans; *Ascochyta* leaf and pod-spotting peas) is key to obtain more stable and attractive yields for farmers.

Protein Quality for Food and Feed The protein quality of legumes is relatively low. Protein quality both for food and feed is important to be able to compete with other high-protein grain sources. In the case of fava beans, the high tannin and vicine/convicine levels make it less attractive; therefore cultivars with lower content are necessary. Lupin has a higher protein yield per unit area than other annual legumes and potential for oil extraction (Schreuder and de Visser 2014). Novel food uses could help in the breeding process to obtain cultivars that can be interesting to consume as food. For instance, lupin is coming as an option for plant-based dairy products with low carbohydrates in high-protein diets, which is the upcoming market demand of meat replacers (Prins and Nuijten 2015). The close work with consumers represents an interesting strategy to reach results in shorter terms as it is shown in the case study with Aarstiderne in Denmark that is presented below.

Case Study: "Aarstiderne[1] an Example of Possible Cooperation of the Private Sector with Breeding Programs"

An interview with Svend Daverkosen, agriculture and environment manager at Aarstiderne, shows his perception on legume production and an example of close cooperation between a Danish company and breeders (Fig. 2.5):

What is your perception about the reduction of legume cultivation in Denmark?

Artificial fertilizers were better for cereals than legumes, so when they entered the market, Danish farmers quickly moved away from legume production. This, combined with the cheap cost of importing legumes from elsewhere, led to a major decline in legume production, first for human consumption and then for animals.

What was the motivation for beginning to experiment with peas and beans at Aarstiderne?

Regulations in the EU have made it easier for gardeners to share seeds informally. An initial project with Nordgen focused on obtaining old varieties and testing them systematically. In 2014, Nordgen started looking for a group to take over this initiative, which coincided with the time that Aarstiderne was looking more toward producing and promoting vegetarian food. So the pea and bean project started with the goal of obtaining more seeds that could be screened and to obtain stable quantities of seeds that could be shared with other companies and breeders. Basically, it constituted a pre-breeding project to revive old varieties.

Since the pea and bean project ended, have you continued to grow legumes at your farms in Krogerup and Barrit?

(continued)

[1]Aarstiderne A/S is a Danish box scheme farm-based company that produces organic vegetables that are delivered in boxes directly to around 60,000 costumers per year in Denmark and the Scandinavian region. Their farms are located in Krogerup and Barrit (Denmark).

Yes, but mostly just for demonstration.

Have you contracted out any of your partner farms to grow legumes on a larger scale than just the test plots?

No, in order to make this happen, a miller needs to get involved (i.e., Aurion). The infrastructure isn't quite there to be growing these varieties on a large scale.

Have you included any Danish-grown legumes in your meal boxes? With what frequency?

Not yet. However, they are about to introduce a new "Pioneer box" to the meal box options. It will include things not yet on the market until now such as the black-seeded amaranth from the University of Copenhagen. It is a way to engage with environmentally focused consumers and to engage them in the selection process, as there will be a mechanism for feedback. They may add some peas to this box, but the details are not yet available.

Which of the legumes you worked with were most promising in terms of yields and agronomic value, convenience of growing and processing, and marketability?

Beans have to be harvested at the perfect moment. If they're too dry, they split with cleaning. There are many climbing varieties of both peas and beans, but this is not practical on a field scale. Thus, the bush peas and beans are best for large-scale production. However, the climbing varieties do have some interesting flavors that are not found in the bush varieties, so there is some potential to grow them for restaurants.

Fig. 2.5 Aarstiderne farm in Krogerup—Denmark

2.2.6.2 Challenge 2: Political Support

Political regulation of the agricultural system from the CAP of the European Commission has great importance at multiple levels. It determines who is entitled to receive financial support; can set up additional funding schemes for specific political goals; and defines the environmental regulation. Hence, the CAP has the power to change both cultivation patterns and markets. The current political incentives are therefore an important parameter when evaluating the motivation for farmers to get involved.

> Discussions for restructuring agricultural subsidies under the CAP reform should include greening initiatives with new crops for diversification and ecological focus areas. There are important reasons to increase subsidization and policy support for diversified legume production in Europe, such as legumes as organic fertilizer and for environmental services.

The organic sector in Denmark is planning to ban conventional straw and manure from organic production. Import of GMOs into organic systems has also been prevented. As a result, organic farmers face nutrient shortages, with few and expensive organic replacements. There is also a push for organic farms to be self-sufficient in nutrient management rather than importing nutrients from outside sources. The main organic sectors in Denmark are dairy, arable, and horticulture systems. Organic organizations developed a working group to devise a strategy that includes crop rotation design, improved nutrient recycling (on the farm and regional scale), green manures and catch crops, biogas, breeding, improved yields, and increased cooperation between organic livestock and arable farms (Oelofse et al. 2013). In this case, the role of policymakers is not for subsidizing legumes but rather for creating a necessity for legumes by regulating the use of synthetic N sources.

The second scenario takes a different approach: providing subsidies to farmers for environmental services. Legumes provide many important environmental services, since the advent of synthetic fertilizers, air, and water quality has been negatively affected by excessive N inputs and runoff (Dakora et al. 2008). Leguminous crops fix N through symbiosis with microorganisms, mostly in the *Rhizobium* genus. The N fixed is not only beneficial for the growing legume crop; it is also released into the soil along with organic matter from the root which reduces leaching and available for the following year's crop. The organic matter released is of high quality because of its high N/C ratio. While in the past many farmers have preferred synthetic fertilizers, breeders have developed legumes with higher N fixation levels by using *Rhizobium*-inoculated soybeans (Siddique et al. 2012). In addition, legumes can help to attract a wide range of plant growth-promoting rhizobacteria (PGPR) that boost growth of plants by mobilizing phosphorous uptake and controlling pathogenic organisms (Vessey 2003). Finally, legumes are ecologically beneficial in a crop rotation with cereals, as increased genetic diversity from year to year decreases pest and disease buildup over time (Siddique et al. 2012).

In terms of policy, the classification of legumes as an "ecological focus area" could incentivize farmers to plant legumes instead of using fallow (Wilbois 2015). In this same regard, the classification of legumes as permitted cover crops to be used on soils could create significant opportunities for legume production.

Case Study: The Influence of Policy and Trade on Production of Peas in Northern Europe

Today, pea is the most widely cultivated legume in the Nordic region (Eurostat 2017). Among the Nordic countries, Denmark had the highest pea production in the period 1974–2003, with a notorious peak (Fig. 2.6). The trends in Danish pea production in this period highlight the role that agricultural policy and trade play in determining production.

In 1974, subsidies were introduced to the common agricultural policy for legume production (Cernay et al. 2015). Immediately afterward, pea production in Denmark began to increase until around 1994 (Fig. 2.6).

A major change in international agricultural policy occurred in 1992 with the signing of the Blair House Agreement, which allowed for non-taxable imports of grain legumes from America to Europe. (Cernay et al. 2015).

Following the signing of this agreement, pea production dropped steadily throughout Europe (Table 2.3) as well as consumption for animal feed (Fig. 2.7). Feed data from the EU from 1993–2008 shows that after 1993, soybean consumption increased by 50%, while peas and beans became less important as feed sources (Table 2.3). By 2005, more than 75% of protein-rich grains used for animal feed were imported from America (GL-Pro 2005). This policy allowing for the cheap import of soy-based feeds, coupled with rising global production of palm kernel and rapeseed, impacted legume production in Europe (Table 2.3).

These results show that policy has great potential to influence production positively if policies and subsidies are put in place to promote European production. As the EU begins to focus more on reducing soy imports from the Americas, there is great potential for policy outcomes favoring European legumes.

2.2.6.3 Challenge 3: Consumer Behavior

Human consumption of pulses in Europe is lower than in most parts of the world. One of the major barriers is the lack of innovation regarding processed legume products with a high level of cooking convenience (Schneider 2002). Despite this challenge, a number of examples from Northern Europe shed light on opportunities for shifting peoples' diets away from meat and toward legume consumption.

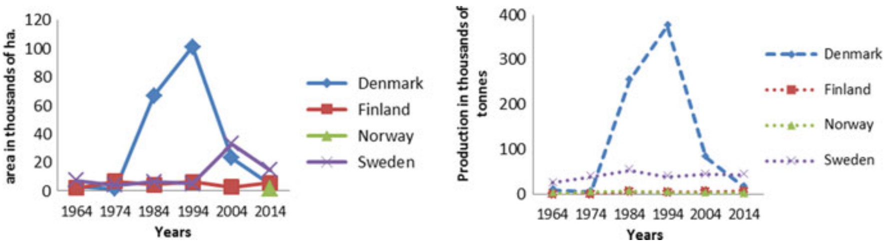

Fig. 2.6 Cultivation area (left) and total annual production (right) of pea (dry) in the Nordic countries from 1964 to 2014

One of the scarce researches on consumer preferences studied the potential to replace parts of the current meat consumption in Sweden with locally produced fava beans. Customers in a restaurant were offered to replace a portion of their meat with a side dish of fava beans. Between 78 and 97% of people accepted to exchange their meat portion, with one of the four alternative fava bean recipes offered (Carlsson 2014). This type of results is indicative that consumers are willing and enthusiastic to taste legume dishes when there is the opportunity.

> Vegetarian, vegan, and "flexitarian" diets are on the rise in Northern Europe. In Denmark, 3.9% of citizens identify themselves as completely vegetarian (Vegetarforening.dk 2010). Supermarkets in Northern Europe have noted increasing demand for vegetarian and vegan foods, with COOP, one of the primary supermarkets in the region experiencing a 30% increase in sales of vegetarian foods from 2014 to 2015 alone.

In Sweden, researchers see great potential in the development of a market for fava beans as fresh green beans or as frozen beans (Nielsen 2016). As such, it is expected that fava bean farmers in Sweden will see high prices for their products in the near future (Nätterlund 2015).

In Germany, researchers have identified a potential market for human consumption of fava beans as a high-quality vegetable protein source (Wilbois 2015). In a report from 2016 analyzing "Nordic Alternative Protein Potentials," it is stated that "Production of protein in practice has considerable future potential, with no shortage of possible supply routes" (Lindberg et al. 2016).

These overall positive expectations were similarly part of the conclusions from the recent project organic gluten-free products, emphasizing fava beans and lupin as good yielding crops with the potential to be further developed for human consumption in Europe (Jacobsen 2016a).

Table 2.3 EU demand for feed ingredients 1993/1994–2007/2008 (million t)

Year	1993	1994	1995	1996	1997	1998	1999	2000	2000	2002	2003	2004	2005	2006	2007
Soybean meal	11.2	12.2	11.4	10.9	11.9	13.2	12.3	13.5	14.7	14.7	14.4	14.4	14.5	14.6	15.3
Field Peas	1.2	1.2	1.1	0.9	1.0	1.2	0.9	0.8	0.7	0.5	0.6	0.8	0.7	0.5	0.2
Field beans	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.1
Lupin	0.09	0.1	0.08	0.1	0.1	0.1	0.1	0.1	0.1	0.09	0.08	0.1	0.09	0.09	0.05

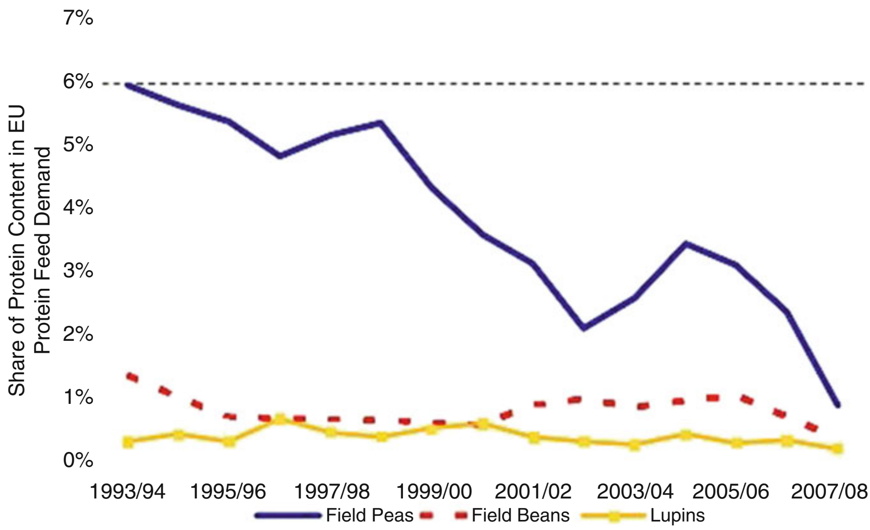

Fig. 2.7 Protein content in total EU protein feed demand 1994-2008 (source LMI International 2009)

Recommendations for Legume Production Issued for Denmark

Faba bean *Expected yield*. 1.7–2.1 t/ha in organic trials in Denmark, with a stability level of 49–60%, the lowest yielding in warmer years (Jacobsen 2016b).

Establishment, soil type, plant density, and harvest. Sown in early spring, in order to utilize the growing season and avoid late maturation. It is also important to achieve a good establishment before potential aphid attacks. Faba bean prefers soils with good water holding capacity, clay or loamy soils, or more sandy soils where irrigation is possible. Sowing depth recommended is

(continued)

5 cm, depending on seed size. Plant density should be 40–60 plants/m^2, with 50 cm between rows. Harvest is no later than mid-September (Bertelsen et al. 2015).

Fertilizers, weeds, pests, and disease management. The most common risks include chocolate spot, leaf spot, aphids, and weevils. Early sowing, choice of cultivar, and a proper crop rotation will lower the risk.

Special sensitivities or tolerances. Cold-tolerant, which makes it a potential winter crop in Northern Europe. Drought-sensitive, especially during flowering, not prone to lodging.

Lupin

Expected yield. 1.5 t/ha in organic trials in Denmark (Jacobsen 2016b), but potential is 4 t/ha.

Establishment, soil type, plant density, and harvest. Early sowing is recommended when soil temperature is 5 °C. Sowing depth is 3–4 cm. Cold or water-logged soils should be avoided. Plant density is 70–80 plants/m^2 for branched and 100–110 plants/m^2 for non-branched cultivars, with a row distance of 24 cm. Branching varieties mature a little later.

Fertilizers, weeds, pests, and diseases management. Lupins utilize well the phosphorous in the soil but can lack manganese in calcium-rich or loose soils which will result in late and nonhomogeneous maturation. Root rot and anthracnose can occur and need to be managed with crop rotation. Mildew can also cause damage in wet climate.

Special sensitivities or tolerances. Highly sensitive to low temperatures, especially around germination. Seeds should be dried directly after harvest.

(continued)

Lentil

Expected yields. 1.5 t/ha in organic trials in Denmark, depending on the variety, with *Pardina* the best yielding with 1.7 t/ha (Jacobsen 2016b).

Establishment, soil type, plant density, and harvest. Lentils should be sown at a depth of 4–6 cm at a density of 120–150 plants/m^2, with a distance between rows of 50 cm. It is not a good competitor for weeds. It prefers loose, well-drained soils. Early establishment will increase yield but with a risk of lodging. After harvest, seeds should be stored only for one season as the seeds slowly break down from oxidation of the phenols in the seed shell.

Fertilizers, weeds, pests, and diseases management. Mildew can cause problems if the plant density is high, and it can be prone to aphid attacks. There is risk of *Sclerotinia sclerotiorim* if lentils follow canola (Jacobsen 2016a).

Special sensitivities or tolerances. Drought-tolerant with low water consumption, will not grow on water-logged soils.

Pea

Expected yields. 2–5 t/ha in organic farming.

(continued)

Establishment, soil type, plant density, and harvest. Peas are relatively tolerant to cold, so they can be sown early, as long as the soil is not too wet, to reduce risk of aphid attacks and drought stress. Pea should not be cultivated on sandy soils unless irrigation is available, especially around the flowering time. Sowing depth is 6–8 cm. Plant density is 90 plants/m^2, in narrow rows.

Fertilizers, weeds, pests, and diseases management. Paying attention to potassium, peas can fixate around 140–170 kg N/ha of which 70 kg N/ha is left in the field residue and roots, half of which could be utilized by the following crop. The worst issues for peas are root fungal infections pea root rot (*Aphanomyos*, *Phytophthora pisi*, and *Sclerotinia sclerotiorum*).

Special sensitivities or tolerances. Peas are drought-sensitive due to their shallow root system.

2.3 Southern Europe

2.3.1 Sustainability of Plant Protein Production

Southern Europe covers an area of 1.35 million km^2 including Italy, Spain, Portugal, Greece, and Southern France among other Mediterranean countries of this country. Agriculture in this area is characterized by a Mediterranean climate affected by drought and salinity stresses. Number of rainy days over the south coast of Spain and the Pyrenean mountains decreased by 30–50%, from 1964 to 1993 (Romero et al. 1999). In Italy, the rainfall fell by 5% in the north and by 15% in the south (Buffoni et al. 1999; Brunetti et al. 2001).

Southern Europe is more vulnerable to climate change compared to other parts of Europe (Intergovernmental Panel on Climate Change 2014). The climatic scenarios for Southern Europe predict that this area will have a high number of severely affected sectors and domains. Europe has experienced several extreme summer heat waves since 2003, which have led to high mortality and economic impacts. Air temperature is projected to increase from 2050 under a high emission scenario.

Many authors studied the effects of climate change on agricultural systems (Rosenzweig and Tubiello 1997; Giorgi and Lionello 2008; Giannakopoulos et al. 2009, Pulvento et al. 2015, Jacobsen 2014). Higher temperature and drought in the Mediterranean region may cause lower yields and the need for climate-proof crops and sustainable agronomic practices (Benlhabib et al. 2014; Jacobsen et al. 2012; Lavini et al. 2014, 2016; Yazar et al. 2015).

Climate changes will exacerbate the pressure on water resources due to considerable competition between different water users; moreover irrigation demand is projected to increase in this area (EEA report 2017). In addition, salinity and flood incidence will increase with climate change (Nichols et al. 2000).

Under this scenario, water becomes a more important resource, since about 86% of world water resources is used to produce food (Hoekstra and Chapagain 2008), which means that food demand heavily impacts on water demand (De Fraiture 2007; Peden et al. 2007). If we analyze the water footprint of protein,[2] we find that milk, eggs, and chicken meat have a value about 1.5 times larger than for pulses. Water footprint for pulses is six times lower than the one for beef (Mekonnen and Hoekstra 2010).

The production process of plant proteins based is more efficient since it requires less inputs in terms of water, soil, and nitrogen compared to meat proteins. By reducing red meat consumption and increasing consumption of protein from vegetable sources, it could be possible to reduce the EU's environmental footprint and to increase health benefits.

2.3.2 *Mediterranean Diet and Product Trends*

The importance of protein crops for human nutrition is first related to their protein content (proteins are the basis of human metabolism). Legumes contain the same protein content of meat with lower quality, two times more protein than cereals, and three times more the one of rice.

High-protein-quality crops like quinoa, amaranth, and buckwheat are lower in protein content than legumes, but the quality of their proteins (composition in essential amino acids) is higher and similar to meat (De Ron et al. 2017).

So, the consumption of a mix of legumes, cereals, and high-quality protein crops can supply to the human body with a proper protein intake and balanced essential amino acids.

The history of plant proteins across Europe is diverse. Geographic and time trends of EU-28 countries suggest that many countries, traditionally reliant upon diets rich in plant proteins, substantially reduced their consumption and production from the 1960s to the turn of the millennium (P2F project).

Traditionally food habits in the Mediterranean area were characterized by the Mediterranean diet (MD) that derives from a millenary exchange of people, habits, and foods from different regions.

Nutritionists developed guidelines to improve the eating habits of consumers in a fair and balanced way of eating that can be represented by the "food pyramid" (Fig. 2.8) which displays the proportions and the frequencies with which foods should be consumed (Altomare et al. 2013).

Legumes are at the base of the pyramid and should be eaten daily. In Mediterranean diet, we find many dishes made with a combination of cereals and legumes that give to the food the necessary balance of quality and quantity of proteins. These dishes, containing cereals and legumes, reach in combination the quality of meat proteins. Today we have the opportunity also to add proteins from quinoa and

[2]The water footprint account the total volume of water needed to produce; it is calculated tacking into account water consumption and pollution.

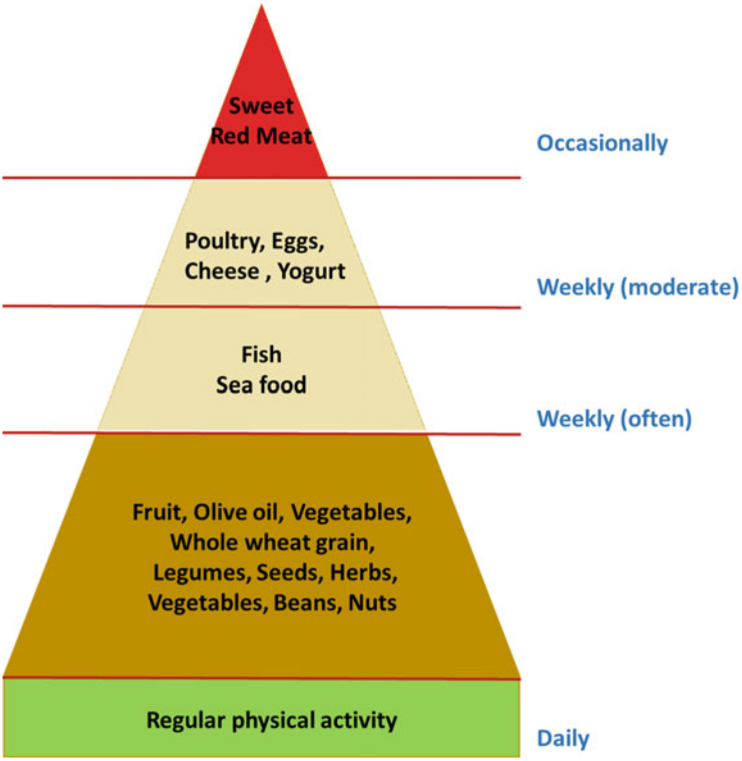

Fig. 2.8 Food pyramid scheme (Oldways Preservation & Exchange Trust 2009)

amaranth that are the only food plants that contain all the essential amino acids, trace elements, and vitamins and contain no gluten.

The progressively globalization of food production, consumption, and diffusion of the Western-type development model in modern times eroded the typical Mediterranean diet and increased risks for human health.

Balanza et al. (2007) analyzed food trends in Mediterranean Europe from 1960 to 2000 and founded an increase in percentage of energy from animal fat, protein, and meat and decreasing percentage of energy provided by plant protein and carbohydrates.

The risk of some diseases like obesity, cancer, diabetes, and cardiovascular disease is higher for people who consume more animal proteins. Processed meats have been classified from World Health Organization as carcinogenic (Bouvard et al. 2015).

Furthermore, the zootechnical sector uses great amount of antibiotics determining antimicrobial resistance.

Lin et al. (2015) compared diets based both on animal and plant proteins diets to evaluate their correlation with obesity and metabolic indicators of cardiovascular disease in young people from European countries and showed BMI z-score and body fat percentage were stronger correlated to animal-based with respect to plant-based protein intakes. Therefore, they suggested that obesity could be prevented with a correct protein food diet.

The low yields of legumes with respect to cereals and the "decoupling" strategies of CAP are the main causes of the decline of protein crops cultivated areas in Europe.

For these reasons, today the EU is aiming at incentive plant-based proteins using agricultural subsidies, more funds for research and innovation, creation of awareness on health diet, and publicity and dissemination.

2.3.3 Plant Protein Biodiversity

With the term protein crops, we define all crops that provide adequate protein content. The main protein crops for human nutrition can be divided into high-protein-level crops like pulses and high-quality protein crops like quinoa, amaranth, and buckwheat.

We know that there is a large number of species of pulses, including many locally produced species, characterized by high genetic diversity used by the small-scale farmers to manage soil and pest. Farmers can also choose from numerous varieties of pulses to select those that are more tolerant to drought and floods and cope with climate change (FAO-International Year of Pulses 2016).

In south Europe we can find today a lack of improved varieties of pulses. Farmers still cultivate local ecotypes characterized by low yield potential, high postharvest losses, inadequate adoption of improved technology, and low profitability, all issues which need to be tackled.

Often these local varieties are characterized by interesting quality traits. For this reason these species and specific traits are studied to be used by breeders for the development of new varieties.

There are associations like Slow Food Italy, who protect local pulses in different regions, protecting domestic biodiversity, by dissemination (enhancement of traditional products, and local edible plant varieties and species) and by the development of specific supply chains.

2.3.4 Cultivated Areas and Production

The total arable land of south Europe in 2014 covered 45% of total south European land (FAOSTAT 2017). In 2015, pulses were cultivated on 2.1% of all European Union arable land (2.2 million ha), and this data increased over the last 3 years.

22.5% of the pulse area was in Spain, followed by Poland and France. This means that 34% of the pulse area was in two south European countries

The total area of pulses and other protein crops in Southern Europe in 2016 accounts for 1,one million hectares (Table 2.4), almost 50% of total European area of protein crops. Pulses are cultivated everywhere in EU except Malta.

France has the highest share (23%) for pea cultivation. In Greece 75.1% of cultivated areas with pulses are covered by other dry pulses (Table 2.5). In Spain there is Almost half (48%) of the area cultivated with "other dry pulses."

France produced the highest quantity of dry pulses in Europe (672,000 t), but this data showed a decreasing trend; its production in 2016 was a quarter compared to 2000. Italy and Spain showed an increasing trend (Table 2.6).

Table 2.4 Production of dry pulses in south Europe (100 ha)

Country/year	2000	2010	2015	2016
Greece	23	25	67	67
Spain	455	447	489	464
France	478	416	269	322
Croatia	8	2	2	2
Italy	68	80	59	82
Cyprus	1	0	1	1
Malta	0	0	0	0
Portugal	24	13	12	11
Montenegro	n.a.	0	0	0
Macedonia	19	13	14	13
Albania	23	14	15	N/A
Total	1099	1101	1143	1143

Eurostat 2017

Table 2.5 Total cultivated area of dry pulses and protein crops producing area in south Europe in 2016 (100 ha)

Country/crop	Pea	Faba bean	Sweet lupin	Other dry pulses and protein crops
Greece	10	5	2	50
Spain	161	46	3	254
France	209	78	8	27
Croatia	1	2	0	0
Italy	14	50	0	17
Cyprus	0	0	0	0
Malta	0	0	0	0
Portugal	0	4	0	8
Montenegro	0	0	0	0
Macedonia	1	13	0	N/A
Albania	N/A	N/A	N/A	N/A

Eurostat 2017

Table 2.6 Dry pulses and protein crops production (100 t)

Country/crop	2000	2010	2015	2016
Greece	36	56	88	87
Spain	409	507	503	641
France	2095	1599	930	673
Croatia	4	3	3	4
Italy	109	159	118	177
Cyprus	2	1	1	1
Malta	0	0	0	0
Portugal	13	7	7	6
Montenegro	n.a.	0	0	0
Macedonia	16	12	13	13
Albania	25	25	28	N/A

Eurostat 2017

In Greece in 2014, 19,360 ha of arable land were dedicated to pulses of which 650 cultivated with grass pea, 5000 with lentil and 5200 with chickpea (ELSTAT 2014).

Buckwheat was cultivated in 2014, on 705 ha in Bosnia and Herzegovina and 350 ha in Croatia (FAOSTAT 2017).

Other high-quality protein crops like quinoa were recently introduced in Europe; the area cultivated with quinoa passed from 0 ha (2008) to 5000 ha (2015), mainly in France, Spain, and the United Kingdom (Bazile et al. 2016).

2.4 Conclusions

Proteins are essential nutrients for the human body to assure a healthy, balanced diet, and protein crops have represented human food source for many centuries.

The mix of high-protein-level crops (pulses) and high-quality protein crops (i.e., quinoa and amaranth) can contribute in a sustainable way to the human protein requirements as a primary and affordable source of proteins and minerals.

We have described the role of protein crops in Europe, demonstrating the importance of plant protein in the human diet. Plant proteins have nutritional and health benefits, and they can cope with climate change and can increase biodiversity and soil fertility.

The production of protein crops can be intensified in a sustainable manner using locally adapted varieties. To boost the availability and consumption of protein crops tolerant to abiotic stresses, breeding programs and specific policies aimed at sustaining both the local and international markets and modern consumption habits should be encouraged.

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References

Adolf VI, Jacobsen SE, Shabala S (2013) Salt tolerance mechanisms in quinoa (*Chenopodium quinoa* Willd.). Environ Exp Bot 92:43–54

Altomare R, Cacciabaudo F, Damiano G, Palumbo VD, Gioviale MC, Bellavia M, Monte AIL (2013) The mediterranean diet: a history of health. Iran J Public Health 42(5):449–457

Anglade J, Billen G, Garnier J (2015) Relationships for estimating N2 fixation in legumes: incidence for N balance of legume-based cropping systems in Europe. Ecosphere 6:1–24

Balanza R, García-Lorda P, Pérez-Rodrigo C, Aranceta J, Bonet MB, Salas-Salvadó J (2007) Trends in food availability determined by the Food and Agriculture Organization's food balance sheets in Mediterranean Europe in comparison with other European areas. Public Health Nutr 10 (2):168–176

Bazile D, Jacobsen SE, Verniau A (2016) The global expansion of quinoa: trends and limits. Front Plant Sci Sect Crop Sci Horticult 3:622

Benlhabib O, Yazar A, Qadir M, Lourenço E, Jacobsen SE (2014) How can we improve Mediterranean cropping systems? J Agro Crop Sci 200:325–332. https://doi.org/10.1111/jac.12066

Bertelsen I, Pedersen T M, Jørgensen K et al (2015) Ny viden og nye muligheder Økologiske hestebønner i mark og stald Seges Økologi GUDP

Bouvard V, Loomis D, Guyton KZ, Grosse Y, El Ghissassi F, Benbrahim-Tallaa L, Guha N, Mattock H, Straif K (2015) Carcinogenicity of consumption of red and processed meat. Lancet Oncol 16(16):1599–1600

Brunetti M, Maugeri M, Nanni T (2001) Changes in total precipitation, rainy days and extreme events in northeastern Italy. Int J Climatol 21(7):861–871

Bues A, Preißel, S, Reckling M, Zander P, Kuhlman K, Topp K, Watson K, Lindström K, Stoddard FL, Murphy-Bokern D (2013) The environmental role of protein crops in the new common agricultural policy

Buffoni L, Maugeri M, Nanni T (1999) Precipitation in Italy from 1833 to 1996. Theor Appl Climatol 63(1):33–40

Carlsson G (2014) Increasing the share of domestic grain legumes in human diets - benefits for cropping and food system sustainabilityIn: Protein from plants in a Nordic Bio-Economy: 11–20

Cernay C, Ben-Ari T, Pelzer E, Meynard J-M, Makowski D (2015) Estimating variability in grain legume yields across Europe and the Americas. Scientific Rep 5:11171

Chemnitz C, Becheva S (2014) Meat atlas: Facts and figures about the animals we eat. Heinrich Böll Foundation, Berlin

Chorley GPH (1981) The agricultural revolution in northern Europe, 1750–1880: Nitrogen, legumes, and crop productivity. Econ Hist Rev 34(1):71–93

Crépon K, Marget P, Peyronnet C et al (2010) Nutritional value of faba bean (Vicia faba L) seeds for feed and food. Field Crop Res 115:329–339

Dakora FD, Spriggs AC, Ndakidemi PA, Belane A (2008) Measuring N 2 fixation in legumes using 15 N natural abundance: Some methodological problems associated with choice of reference plants. In: Biological Nitrogen Fixation: Towards Poverty Alleviation through Sustainable Agriculture. Springer, Dordrecht, pp 43–45

Danish Agriculture & Food Council (2014) Facts and figures about Danish agriculture and food. In: Knowledge - Growth - Balance. Danish Agriculture & Food Council, Copenhagen, p 36

Daryanto S, Wang L, Jacinthe PA (2015) Global synthesis of drought effects on food legume production. PLoS One 10(6):e0127401

De Fraiture C (2007) Integrated water and food analysis at the global and basin level. An application of WATERSIM. Water Resour Manage 21(1):185–198

De Ron AM, Sparvoli F, Pueyo JJ, Bazile D (2017) Protein crops: Food and feed for the future. Front Plant Sci 8:105

De Visser C (2013) Protein crops The agricultural European Innovation Partnership (EIP-AGRI). European Commission, Brussels

DTU Fødevareinstituttet (Danmarks Tekniske Universitet) (2017) Fødevaredata ver. 2. (Online) Available at http://frida.fooddata.dk/ShowFood.php?foodid=741&1. Accessed 07 Apr 2017
EEA report n1 (2017) Climate change, impacts and vulnerability in Europe (2014)
European Central Bank Eurosystem (2017) In: https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-dkk.en.html. European Central Bank. Accessed 28 Nov 2017
Eurostat (2016) Agriculture, forestry and fishery statistics 2016 ed: Luxemburg (DOI: https://doi.org/10.2785/147560)
Eurostat statistic (2015). Available at http://ec.europa.eu/eurostat/statistics-explained/index.php/Dry_pulses_in_EU_agriculture_-_statistics_on_cultivation,_production_and_economic_value. Accessed 28 Jul 2017
Eurostat (2017) Database crop production. The website of Eurostat, Luxembourg. Available at http://ec.europa.eu/eurostat/web/agriculture/data/database
ELSTAT (2014) Hellenic Statistical Authority. 2014 Annual agricultural statistical survey
FAO (2011) World livestock 2011: Livestock in food security, Rome
FAO-International Year of Pulses (2016). Available at: http://www.fao.org/pulses-2016/en/. Accessed 1 Aug 2017
FAOSTAT (2017) Livestock primary. In: Food and Agriculture Organization of the United Nations ed.
Farmtalonline.dlbr.dk (2016) Hestebønner (Online). Available at https://farmtalonline.dlbr.dk/Kalkuler/VisKalkule.aspx?Prodgren=K_3130&Forudsaetninger=31-12-2017;K_3130;2;3;2;1;2;1;1;1;3;1;n;n;0;n Accessed 12 Apr 2017
Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Balzer C (2011) Solutions for a cultivated planet. Nature 478(7369):337–342
Giannakopoulos C, Le Sager P, Bindi M, Moriondo M, Kostopoulou E, Goodess CM (2009) Climatic changes and associated impacts in the Mediterranean resulting from a 2 C global warming. Glob Planet Chang 68(3):209–224
Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. Glob Planet Chang 63(2):90–104
GL-Pro (2005) Guidelines for growing legumes in Europe In: GL-Pro project ed. www.grainlegumes.com/gl-project GL-Pro project
Hoekstra AY, Chapagain AK (2008) Globalization of water: sharing the planet's freshwater resources. Blackwell Publishing, Oxford
Intergovernmental Panel on Climate Change (2014) Climate change 2014–impacts, adaptation and vulnerability: Regional aspects. Cambridge, Cambridge University Press
Jacobsen SE (2014) New climate-proof cropping systems in dry areas of the Mediterranean Region. J Agron Crop Sci 200(5):399–401
Jacobsen SE (2016a) Screening af nye glutenfri afgrøder til dyrkning i Danmark I Markforsøg på Højbakkegård. KU-PLEN, Tåstrup Projekt Glutenfri Økologi – fra muld til mund GUDP
Jacobsen SE (2016b) Screening af nye glutenfri afgrøder til dyrkning i Danmark II Markforsøg hos landmænd Projekt Glutenfri Økologi—fra muld til mund GUDP
Jacobsen SE, Mujica A, Jensen CR (2003) The resistance of quinoa (*Chenopodium quinoa* Willd.) to adverse abiotic factors. Food Rev Int 19:99–109
Jacobsen SE, Jensen CR, Liu F (2012) Improving crop production in the arid Mediterranean climate. Field Crop Res 128:34–47
Kammlade S, Sotelo S, Achicanoy H, Bjorkman A, Navarro-Racines C (2017) Country exploration. In http://ciat.cgiar.org/the-changing-global-diet/country-exploration/, Version 10 March 2017 CIAT
Kharas H (2010) The emerging middle class in developing countries. Global development outlook. OECD Development Center Working Paper No 285
Köpke U, Nemecek T (2010) Ecological services of faba bean. Field Crop Res 115(3):217–233
Kontturi M, Laine A, Niskanen M, Hurme T, Hyövelä M, Peltonen-Sainio P (2011) Pea–oat intercrops to sustain lodging resistance and yield formation in northern European conditions. Acta Agric Scand B Soil Plant Sci 61(7):612–621

Lavini A, Pulvento C, d'Andria R, Riccardi M, Choukr-Allah R, Belhabib O, Yazar A, İncekaya Ç, Metin Sezen S, Qadir M, Jacobsen SE (2014) Quinoa's potential in the Mediterranean region. J Agron Crop Sci 200(5):344–360

Lavini A, Pulvento C, d'Andria R, Riccardi M, Jacobsen SE (2016) Effects of saline irrigation on yield and qualitative characterization of seed of an amaranth accession grown under Mediterranean conditions. J Agric Sci 154(5):858–869

Lin Y, Mouratidou T, Vereecken C, Kersting M, Bolca S, De Moraes ACF, Labayen I (2015) Dietary animal and plant protein intakes and their associations with obesity and cardio-metabolic indicators in European adolescents: the HELENA cross-sectional study. Nutr J 14 (1):10

Lindberg JE, Lindberg G, Teräs J, Poulsen G, Solberg SØ, Tybirk K, Jóhannsson R (2016) Nordic alternative protein potentials: mapping of regional bioeconomy opportunities. Nordic Council of Ministers

LMC International (2009) Evaluation of measures applied under the Common Agricultural Policy to the protein crop sector. Main Report. http://ec.europa.eu/agriculture/eval/reports/protein_crops/index_en.htm (European Commission, 2009) Accessed September 2014

Maracchi G, Sirotenko O, Bindi M (2005) Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe. In: Increasing Climate Variability and Change. Springer, Dordrecht, pp 117–135

Mekonnen MM, Hoekstra AY (2010) A global and high-resolution assessment of the green, blue and grey water footprint of wheat. In: Value of Water Research in Report Series No 42. UNESCO-IHE, Delft, The Netherlands

Nätterlund H (2015): Growing field beans: Experiences from Sweden. In: Kammlade S, Sotelo S, Achicanoy H, Bjorkman A, Navarro-Racines C (2017) Country exploration. Version 10 March 2017 CIAT

Nichols DS, Olley J, Garda H, Brenner RR, McMeekin TA (2000) Effect of temperature and salinity stress on growth and lipid composition of Shewanella gelidimarina. Appl Environ Microbiol 66(6):2422–2429

Nielsen KM (2016) Spis hestebønne. http://okologi.dk/newsroom/2016/09/hesteboenner-konsumtterlun

Oelofse M, Jensen LS, Magid J (2013) The implications of phasing out conventional nutrient supply in organic agriculture: Denmark as a case. Organic Agriculture 3:41–55

Oldways Preservation & Exchange Trust (2009) Mediterranean diet pyramid. https://oldwayspt.org/history-mediterranean-diet-pyramid. Accessed 1 Aug 2017

Ozturk T, Ceber ZP, Türke M, Kurnaz ML (2015) Projections of climate change in the Mediterranean Basin by using downscaled global climate model outputs. Int J Climatol 35 (14):4276–4292

Peden D, Tadesse G, Misra A K, Ahmed FA, Astatke A, Ayalneh W, Mpairwe D (2007) Water and livestock for human development. (No H040205) International Water Management Institute

Prins U, Nuijten E, (2015) Using a multi-actor approach to getting lupins 'back on the menu'in The Netherlands: involving breeders, farmers, food and feed industry and consumers

Pulvento C, Lavini A, Riccardi M, d'Andria R, Ragab R (2015) Assessing amaranth adaptability in a Mediterranean area of south Italy under different climatic scenarios. Irrig Drain 64(1):50–58

Riccardi M, Pulvento C, Lavini A, d'Andria R, Jacobsen SE (2014) Growth and ionic content of quinoa under saline irrigation. J Agron Crop Sci 200(4):246–260

Rodziewicz P, Swarcewicz B, Chmielewska K, Stobiecki M, Wojakowska A (2014) Influence of abiotic stresses on plant proteome and metabolome changes. Acta Physiol Plant 36:1–19

Romero R, Ramis C, Guijarro JA, Sumner G (1999) Daily rainfall affinity areas in Mediterranean Spain. Int J Climatol 19(5):557–578

Rosenzweig C, Tubiello FN (1997) Impacts of global climate change on Mediterranean agrigulture: Current methodologies and future directions. Mitig Adapt Strateg Glob Chang 1(3):219–232

Schneider AV (2002) Overview of the market and consumption of pulses in Europe. Br J Nutr 88 (3):S243–S250

Schreuder R, de Visser C (2014) Report: EIP-AGRI Focus Group: Protein Crops Final Report

SEGES (2017) Priser aktuelle og bagudrettet, Om Farmtal Online. (Online) Available at: https://farmtalonline.dlbr.dk/Navigation/NavigationTree.aspx Accessed 27 Jul 2017

Shehata NA, Darwish N, El-Nahry F, Abdel Razek FA (1988) Supplementation of wheat flour with some local legumes. Mol Nutr Food Res 32(1):1–8

Siddique KH, Johansen C, Turner NC, Jeuffroy MH, Hashem A, Sakar D, Alghamdi SS (2012) Innovations in agronomy for food legumes. A review. Agron Sustain Dev 32(1):45–64

Simpson HC, Lousley RS, Greekie M, Hockaday TDR, Carter RD, Mann JI (1981) A high carbohydrate leguminous fibre diet improves all aspects of diabetes control. Lancet 1:1–4

Stoddard FL (2013) Legume Futures Report 2: The case studies of participant expertice in Legume Futrures. In: wwwlegumefuturesde Legume Futures ed, pp 45 Helsinki

Tharanathan RN, Mahadevamma S (2003) Grain legumes— a boon to human nutrition. Trends Food Sci Technol 14:507–518

Toker C, Yadav SS (2010) Legume cultivars for stress environments. In: Yadav SS, McNeil DL, Redden R, Patil SA (eds) Climate change and management of cool season grain legume crops. Springer, Dordrecht, pp 351–376

United Nations, Department of Economic and Social Affairs, Population Division (2017) World population prospects: The 2017 Revision, Key findings and advance tables. Working Paper N° ESA/P/WP/248

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255(2):571–586

Vikinge Center, R (2017) "Storgårdens afgrøder". In: http://www.ribevikingecenter.dk/da/viden/storgaardens-afgroeder.aspx

Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG (1997) Human alteration of the global nitrogen cycle: sources and consequences. Ecol Appl 7:737–750

Wilbois KP (2015) Sustainable and regional supply with organic grain legumes in Europe. In: FiBL Deutschland, FiBL Deutschland (ed) FiBL

Yazar A, Incekaya C, Metin Sezen S, Jacobsen SE (2015) Saline water irrigation of quinoa (Chenopodium quinoa) under Mediterranean conditions. Crop Pasture Sci 66(10):993–1002. https://doi.org/10.1071/CP14243

Zaccardelli M, Lupo F, Campanile F, Infantino A (2010) Leguminose minori (cece, lenticchia, cicerchia, fava). Progetto di ricerca per potenziare la competitività di orticole in aree meridionali

Chapter 3
Hypersaline Water for Alternative Crop Irrigation in Iran

Masoumeh Salehi

Abstract Iran water scarcity threatens food security, and in addition to that urbanization, land degradation and reducing water quality are main threats to agricultural production of Iran. Research in gene transfer and improving salt tolerance crops are progressing slowly, which mean that alternative crop and forage for farming in saline condition could be considered. This chapter summarizes a recent experiment in using four halophytes (*Chenopodium quinoa*, *Panicum antidotale*, *Kochia scoparia*, and *Salicornia* spp.) as food, forage, and oil seed in an intensive agriculture system. Results of experiment and demonstration farm showed that halophytes could be used as commercial alternative crops for improving food security with water salinity above 10 dS m^{-1} and reduce pressure on fresh water resources. Quinoa production is commercial with water salinity from 10 to 17 dS m^{-1} (2–3 t ha^{-1} seed yield). Agriculture ministry program is to extent quinoa cultivation to 30000 ha and increase the yield in farmer's field in 2022. *Panicum* and *Kochia* could also be considered for producing forage with saline water (14–20 dS m^{-1}). *Salicornia* spp. showed high potential for producing 0.5–3 t ha^{-1} seed yield and 60–160 t DM ha^{-1}, and then it could be considered for forage and oil seed production in the coastal area.

Keywords Forage · Halophytes · Quinoa · *Salicornia* · Food security

3.1 Introduction

Iran covers an area of 1648 million square kilometers and is the 18th largest country of the world. The average annual rainfall of the country is 250 mm with less than 50 mm in the Central Plateau to more than 1600 mm on the Caspian coastal plain, and 71% of rainfall is evaporated. The average annual potential evaporation of the

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country is very high, ranging from less than 700 mm in the Caspian coastal plain to over 4000 mm in the southwestern part of the Khuzestan and Central Plateau. Based on the latest estimates given in 2013, the area under annual field crop is 11.38 million hectares, 52% under irrigated crops, and 47% under rainfed (Ahmadi et al. 2015). In Iran 5 and 17% of current agriculture lands are located in very poor and unsuitable areas (Mesgaran et al. 2016). The most limiting factor for cropping in Iran is low soil organic carbon, steep slope, high soil sodium content, and insufficiency of water as a major obstacle of agriculture development (Madani et al. 2016). Almost 6.8 ha affected by salinity, of this 4.3 affected by salinity more than 8 and just have salinity limitation in which 1.1 million ha having soil salinity (ECe) 8–16 dS m^{-1}, more than 2.4 million ha having ECe 16–32 dS m^{-1}, and 660,000 ha having ECe greater than 32 dS m^{-1} (Momeni 2010).

Ancient Iranian were successful in harvesting, controlling, and using water, but now, Iran is facing water scarcity problems, dry lakes, declining groundwater levels, decreasing water quality, desertification, soil erosion, and dust storm (Madani et al. 2016). Iranian farmers consume a considerable amount of groundwater for irrigation to compensate surface water deficit. Currently more than 55% of total water demand is satisfied through groundwater pumping, and overpumping of water caused almost 50% of plains in unfavorable condition (Madani et al. 2016). Overpumping of groundwater resulted in groundwater table decline and degrades water quality. Change in water salinity during the period of 1990–2000 in Yazd-Ardakan subbasin in Central Plateau of Iran showed that salinity of groundwater has doubled in some areas (Dehghany et al. 2003).

In Iran salinity of surface water is associated to climate condition and geological characteristics of river basin. Total volume of brackish and saline surface water which total dissolved salts is greater than 1500 mg l^{-1} is equal to 12.88 Km^3 which is about 12% of the renewable surface water resources of the country (Cheraghi 2012). Evaluation of brackish and saline groundwater in the country showed that out of 609 plains, 311 plains is saline, and the Central Plateau basin with 109 plains has the highest area of brackish and saline water (almost 26% of harvesting groundwater is saline) (Cheraghi 2012).

In Iran 22% of cultivated lands are very poor or unsuitable for agriculture, and due to increasing salinity of brackish water resources as a result of overpumping of groundwater, more salt-tolerant crops such as pistachio are being introduced in the region with appropriate climate condition. Still there are other potentials for saline water use in Iran; halophyte farming and aquaculture are considered for increasing food security. Halophytes are plants that have ability to complete their life cycle in 200 mM NaCl (Panta et al. 2014). Almost 11.1% of world flora are halophytes with 3640 species (Yensen 2008). Halophytes species of Iran belonging to 365 species, 151 genera and 44 families (Akani 2006). Halophytes can grow in various climate conditions. Many of them adapted in salt marshes where there is a high concentration of salty water. Some halophytes are adapted near desert environments where water supplies are limited and very saline, some of them are observed on cliffs and dunes near the ocean with high water requirement, and some of them have wide adaptability (Hamed et al. 2014). The most important aspects of Iranian halophytes are their

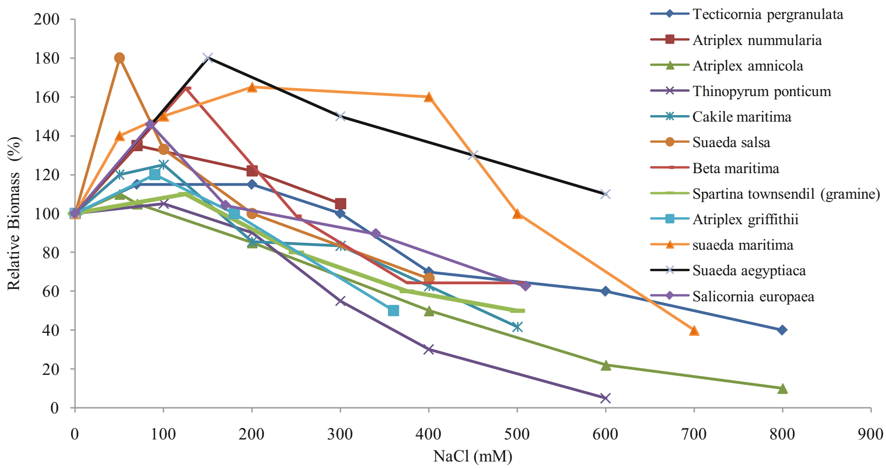


Fig. 3.1 Relative biomass production (%) of halophytes under NaCl (mM) stress. *Tecticornia pergranulata* (Short and Colmer 1999), *A. nummularia* (Greenway 1968), *A. amnicola* (Aslam et al. 1986), *Thinopyrum ponticum* (Jenkins et al. 2010), *Cakile maritima* (Debez et al. 2006), *Suaeda salsa* (Liu et al. 2006), *A. griffithii* (Khan et al. 2000), *S. maritime* (Flowers and Colmer 2008), *S. aegyptiaca* (Askari et al. 2006), *S. europaea*, *Beta maritime*, and *Spartina townsendii* (Koyro and Lieth 2008)

diversity of functional type and adaptation strategies. A facultative halophyte is a plant which can live in salty condition, and slope of biomass production with increasing salinity is very slow in comparison to agricultural crop, and obligate halophytes need salts to produce high yield. Facultative halophytes need fresh water or 100–200 mM saline water for optimum biomass production, but obligate halophytes need 200–300 mM NaCl (Fig. 3.1). Increasing salinity on growth media of halophytes improves growth rate and biomass production, but there is diversity among halophytes, for example, optimum growth rate of *Suaeda aegyptiaca* and *Suaeda salsa* occurred at 150 and 50 mM NaCl (Askari et al. 2006; Liu et al. 2006), but in *Suaeda maritima*, the optimum growth rate occurred at 200–400 mM NaCl (Flowers and Colmer 2008) (Fig. 3.1).

Human activity caused global warming and climate change and threatens agricultural production. Water quality and quantity decline are the main constraints to food security and occupation and cause social problems. Biosaline agriculture is one of the methods for agricultural production using saline soil and water. In this method of agriculture, halophyte cultivation under saline condition with optimum irrigation and soil management is considered.

Rehabilitation of saline environment is the well-granted project by the Iran government. *Atriplex canescens* came to Iran in 1961 for rangeland rehabilitation of Qazvin. Establishment and biomass production were very successful after that in 1981 *Atriplex* replaced other plants. *Atriplex* produce remarkable biomass under very harsh environment, but propagation and negative effect on native species were the main problems and restrict its cultivation to a very saline area. *Atriplex* cultivated

260 ha in the North Khorasan, 40 ha in Mahalat, and 1000 ha in Golestan. *Haloxylon* cultivated 10 ha in Semnan, 893 ha in the South Khorasan, and 120 ha in Aran and Bidgol. *Nitraria* was cultivated in Aran and Bidgol and 200 ha in Kavir Meyghan. But halophyte farming in an intensive agriculture system is not common, and most salinity research projects were limited to conventional crops, and limited research focused on agronomic package for halophyte farming, and there is no funding for basic research on halophyte farming. In Iran water with salinity above 10 and 8 dS m^{-1} is not economic for growing cereal and forage, respectively. Then water with 10 dS m^{-1} and higher could be considered for halophyte farming. Halophytes based on economical yield production under saline condition separated in two main groups. Halophytes grow in seawater salinity (above 20 dS m^{-1}) such as *Salicornia* spp., and halophytes can produce economic yield in water salinity range 10–20 dS m^{-1} such as *Panicum antidotale*, *Kochia scoparia*, and *Chenopodium quinoa*. This review summarizes recent progress in using hypersaline water for halophyte farming in an intensive agriculture system as food, forage, and oil seed crop.

3.2 Halophytes for Improving Food Security

There are more than 50,000 edible plant species in the world, yet a few of them contribute significantly to food supplies. Rice, maize, and wheat are the main sources of calories and protein for human (Loftas and Ross 1995). Oil, wheat, and rice consumption per capita in Iran is 19, 167, and 40 kg. Iranians use ten million ton wheat and 1.2–1.4 million ton oil annually, and wheat has the main role for food security, and almost 95% of oil requirement and one million ton rice were imported to the country. Quinoa is a facultative halophyte, and some varieties are able to complete life cycle at 400 mM salinity (Hariadi et al. 2011; Razzaghi et al. 2011b). Quinoa growth was stimulated by moderate salinity (10 dSm^{-1}) (Brakez et al. 2013; Jacobsen et al. 2003; Koyro et al. 2008) and ten times more water-efficient in terms of protein production than rice (Bazile et al. 2015). Among halophytes, *Salicornia* is considered because of 20–35% high quality oil and producing 2 t ha^{-1} seed (equal to soybean and safflower with fresh water resources) in seawater salinity (Fig. 3.2) (O'Leary et al. 1985; Anwar et al. 2006).

3.2.1 Chenopodium quinoa

Quinoa has been cultivated in the Bolivian and Peruvian Andean region for 7000 years (Garcia et al. 2015). Worldwide interest on this crop is increasing because of high nutritional quality (Nowak et al. 2015; Jacobsen 2003; Repo-Carrasco et al. 2003). Quinoa has a high protein content and an optimal balance of amino acids with high amount of lysine and methionine and high amount of fiber and minerals such as calcium and iron (Abugoch James 2009). It contains antioxidants

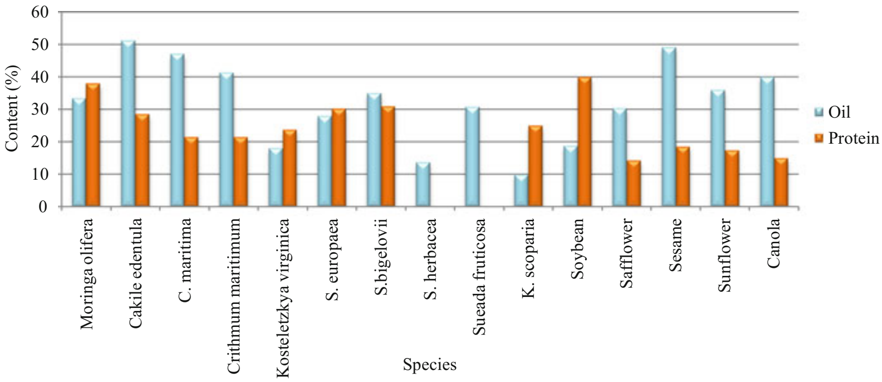


Fig. 3.2 Protein and oil content of halophytes and glycophytes in oil seeds

such as polyphenols (Nsimba et al. 2008). Quinoa is gluten-free and suitable for celiac patients, and whole grain consumption prevents type 2 diabetes and because of low glycemic index can replace common cereals in diabetes diet (de Munter et al. 2007; Zevallos et al. 2015). Quinoa is interest in Iran for high tolerance to abiotic stress and as a new crop for saline area and in rotation with cereal in rainfed area.

Emergence of quinoa with saline water in soil and cocopeat was evaluated, and results showed that emergence reduction slope in sandy loam soil and cocopeat was 6.76 and 8.25% for each unit of salinity increase, and the threshold was 0.03 and 9.52 dS m^{-1}, respectively (Fig. 3.3). Based on modified discount function (Steppuhn et al. 2005), 50% of emergence reduction occurred at 6.35 and 15.04 dS m^{-1} in soil and cocopeat, respectively (Salehi et al. 2017b). Although quinoa could be germinated up to 400 mM salinity, the emergence stage is very sensitive to salinity (Hariadi et al. 2011; Gómez-Pando et al. 2010).

Evaluation of eight species of halophytes during germination stage showed that halophytes are sensitive during seedling stage (Xianzhao et al. 2013). Halophytes species have diversity for germination under saline condition (200–1000 mM) (Gul et al. 2013). Halophyte grass germination occurred from 100 to 500 mM (Gulzar and Khan 2001). Although they can complete life cycle in saline area, some of them are sensitive during emergence, and they can germinate when suitable time and place occurred (Barrett-Lennard et al. 2016). For quinoa it would be better to use a transplanting method or coverage of seed with suitable materials under very saline conditions for good establishment.

High diversity was observed among sowing dates for time to anthesis, and a plant needs twice more GDD for flowering at 14-h day length (Table 3.1, Fig. 3.4). Evaluation of photoperiod sensitivity of two quinoa cultivars showed that quinoa is a quantitative short-day plant for flowering (Bertero et al. 1999). Photoperiod sensitivity in the flowering stage was lower than seed filling period. Three hours increasing in photoperiod increased GDD two and four times in flowering and seed filling stage, respectively. Bertero et al. (1999) reported that photoperiod and temperature after anthesis affect seed growth. Although quinoa is a qualitative

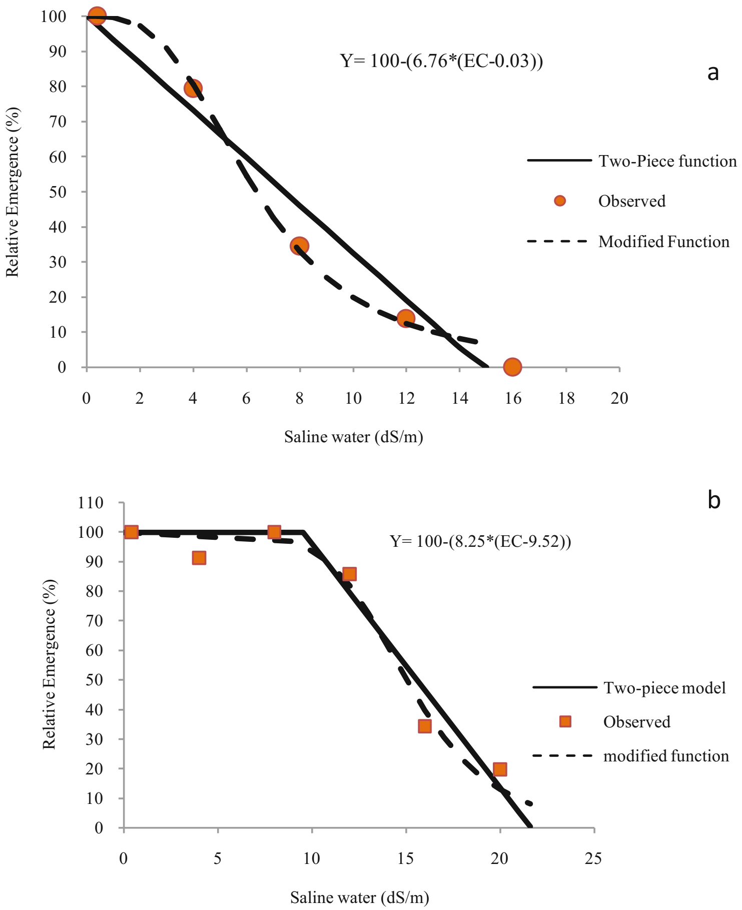


Fig. 3.3 Quinoa response to saline water in the emergence stage in soil (**a**) and cocopeat (**b**)

short-day plant, it was sown in Italy, Denmark, and Turkey as a spring crop and ripped when photoperiod reached to 15–16 h (Lavini et al. 2014; Razzaghi et al. 2011a, Bazile et al. 2015). Quinoa is a short-day quantitative response to photoperiod. This means that longer day extent duration of some growth stage but flower in all the range of photoperiod, and the duration of development is sensitive to temperature (Bazile et al. 2015). This experiment showed that 2.5 hours increasing photoperiod prolonged 19 days, time to flowering (Table 3.1, Fig. 3.4). Because of longer vegetative growth stage in long photoperiod, plants produce more biomass (Table 3.1). In February 24 sowing date, quinoa produced 65 g plant^{-1} biomass in comparison to 41 g plant^{-1} on August 22. The effect of sowing date was not significant on plant height and lateral stem number up to March 7 sowing date, but plants produce more lateral stem numbers in Feb sowing date (Table 3.1). Protein

Table 3.1 Effect of sowing date on phenological and agronomic traits of quinoa

	Sowing date							
	Aug 22	Sep 6	Sep 26	Oct 7	Oct 24	Feb 24	March 7	March 30
Phenological stage								
Emergence	5	6	6	7	9	7	6	7
Floral initiation	32	36	37	Frost damage		41	41	39
Flowering	56	56	77			75	61	74
Color change	68	70	Frost damage			112	105	94
Harvesting	108	123			146	132	126	110
Measured traits								
Seed yield (kg ha^{-1})	2343 a	0.56	No seed	No seed	No seed	1637 ab	1478 ab	680 b
1000 seed weight (g)	2.93 a	–	–	–	–	1.67 b	1.36 bc	1.16 c
Plant height (cm)	91.53 a	–	–	–	–	89.06 a	85.7 ab	80.2 b
Biomass (g plant^{-1})	41.55 b	–	–	–	–	65.23 a	42.93 b	14.91 c
Lateral stem number	18.13 ab	–	–	–	–	22.63 a	20.06 ab	13.10 b
Seed protein content	18	–	–	–	–	15	–	–
Protein yield (kg ha^{-1})	421.74	–	–	–	–	245.55	–	–

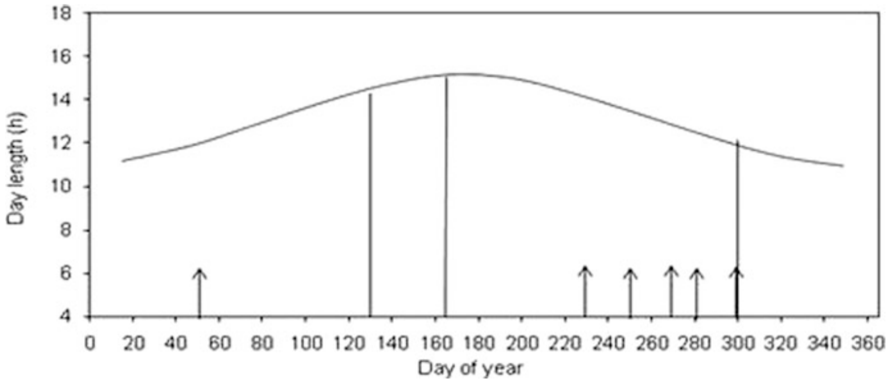


Fig. 3.4 Flowering time of quinoa at different sowing dates. Short and long vertical lines showing sowing date and flowering time, respectively

yield of quinoa was 421 kg ha^{-1} and 245 kg ha^{-1} in August 22 and February 24 sowing date, respectively (Salehi et al. 2016b).

Grain filling is sensitive not only to low (lower 20 °C) but also to high temperature. Titicaca started flowering 50–77 days after sowing in different sowing dates

Table 3.2 Average measured traits of different *Salicornia* species under saline condition (different letters in each rows showing the significant differences based on LSD test at 5% level).

Traits	*Salicornia* species							
	S. sinus-persica	S.bigelovii-red	Golestan accession	S.bigelovii-china	*S. europaea*	Urmia accession	*S.persica*	*S. bigelovii*
Shoot fresh weight (g/transplant)	6446 cd	8345 a	5114 d	7871 ab	3208 e	3546 e	6918 bc	5678 cd
Shoot dry weight (g/transplant)	871 cde	1618 a	993bcd	1625 a	719 de	696 e	1268 b	1146bc
Plant height (cm)	77.3 a	53.9bc	56.8 b	48.8 cd	43.6 d	47.7 cd	78.1 a	44.8 d
Spike length (cm)	12.8 bc	14.8 a	9.4 e	10.9 de	11.5 cd	11.2 cd	11.6 bcd	13.4 ab
Spike dry weight (g/spike)	1.64 bc	3.39 a	0.55 d	1.58 bc	1.25 cd	0.68 d	1.27 cd	2.21 b
No. seed per spike	169 ef	341 a	189 de	209 cd	243 bc	244 bc	145 f	255 b
Spike diameter (mm)	4.46 b	5.43 a	3.03 c	5.63 a	4.41 b	3.13 c	4.45 b	5.16 ab
Spike per transplant	4760 bc	2980 c	14,189 a	2616 c	4718 bc	13,659 a	7976 b	4271 c
1000 seed weight (mg)	0.37 e	1.00 ab	0.43 e	0.93 b	0.79 c	0.34 e	0.63 d	1.06 a
Seed yield (t/ha)	0.79 e	3.65 a	0.68 e	2.25 c	2.29 c	0.57 e	1.30 d	2.80 b
Seed to shoot weight (%)	0.91	2.25	0.68	0.35	3.19	3.23	1.02	2.44

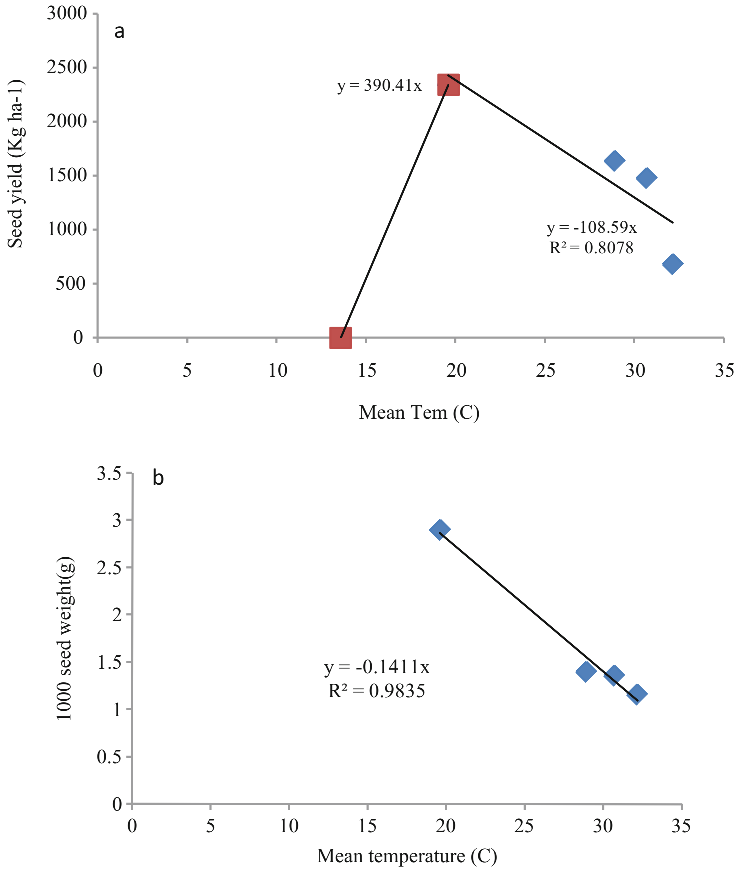


Fig. 3.5 Quinoa seed yield (**a**) and 1000 seed weight (**b**) response to mean temperature during seed filling period

(Table 3.2). Mean temperatures during seed filling at different sowing dates were 19.6, 13.6, frost damage (−4 °C), 28.91, 30.69, and 32.15 at August 22, September 6, September 26, February 24, March 7, and March 30 (Fig. 3.5). Seed yield was 0.56 g m^{-2} with mean temperature of 13.6 °C during seed filling on September 6 sowing date. On March 30 sowing date, high temperature (32.15 °C) reduced seed yield (58% in comparison to February 24 sowing date) (Fig. 3.5a). Increasing 1 °C of temperature during this growth stage reduced yield up to 108 kg ha^{-1} (Fig. 3.5b). Increasing 10 °C during seed filling period reduced almost 1.4 g of 1000 seed weight (Fig. 3.5b). Seed yield reduction with decreasing mean temperature during seed filling from 20 °C was 390 kg $°C^{-1}$ and with increasing temperature was 108 kg $°C^{-1}$ (Salehi et al. 2016b).

Biomass accumulation of quinoa increased sharply after flora initiation. Shoot dry weight increased from 40 g per plant during 40 days (from 10 days after sowing to 50 days after sowing) (Fig. 3.6a), and plant height increased 70 cm during 40 days

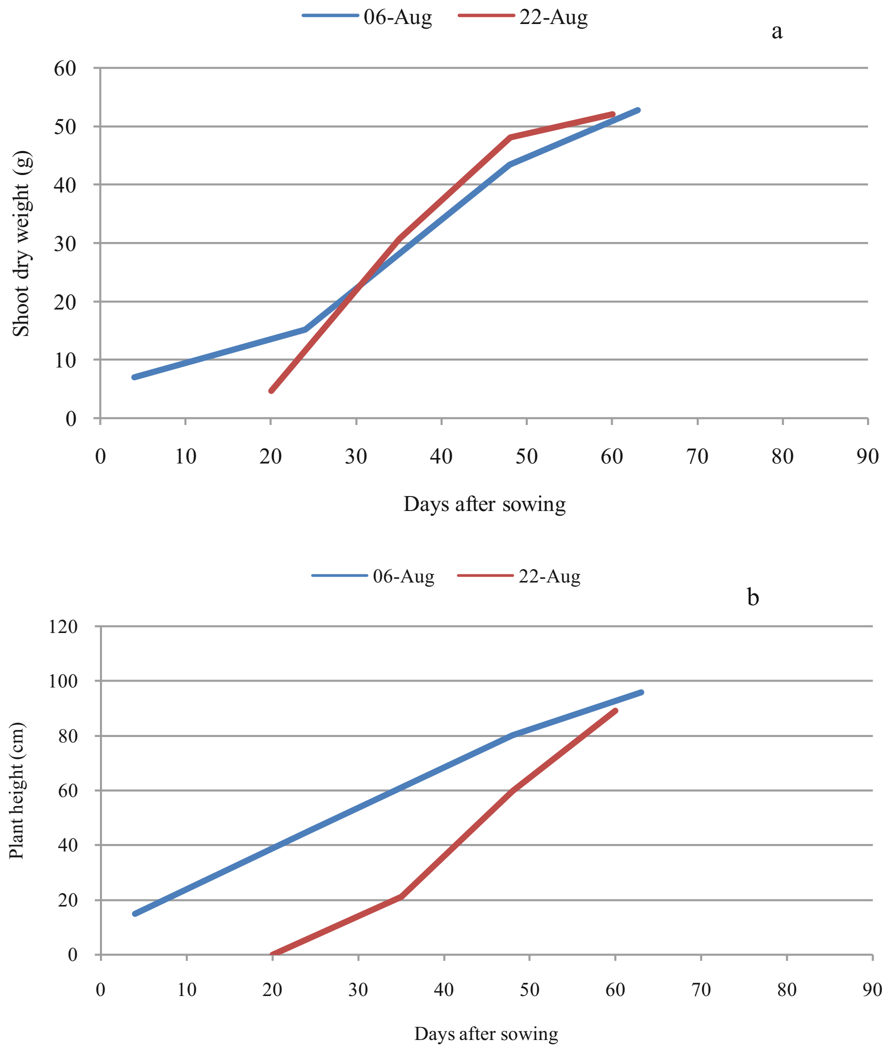


Fig. 3.6 Biomass accumulation (g) (**a**) and Plant height (cm) (**b**) trend during the season at 6 and 22 Aug sowing date (Irrigated with 14 dS m^{-1} saline water)

(Fig. 3.6b). In the both sowing dates (August 6 and 22), shoot dry biomass and plant height reached the max amount at the same time (60 days after sowing), but anthesis and ripening stages delayed 15 days (Fig. 3.7) (Salehi et al. 2016a).

Spodoptera exigua larva damage leaves during flora initiation stage (Fig. 3.8). For controlling of the larva, pesticide should be used after observing the damage and pesticide should repeat 10 days later. This larva is the main pest of potato, sugerbeet and corn in Iran (Salehi et al. 2016b).

Fig. 3.7 Six (left) and 22 Aug (right) sowing date of quinoa which is harvesting by field technician (irrigated with 14 dS m^{-1} saline water)

Fig. 3.8 *Spodoptera exigua* larva damage

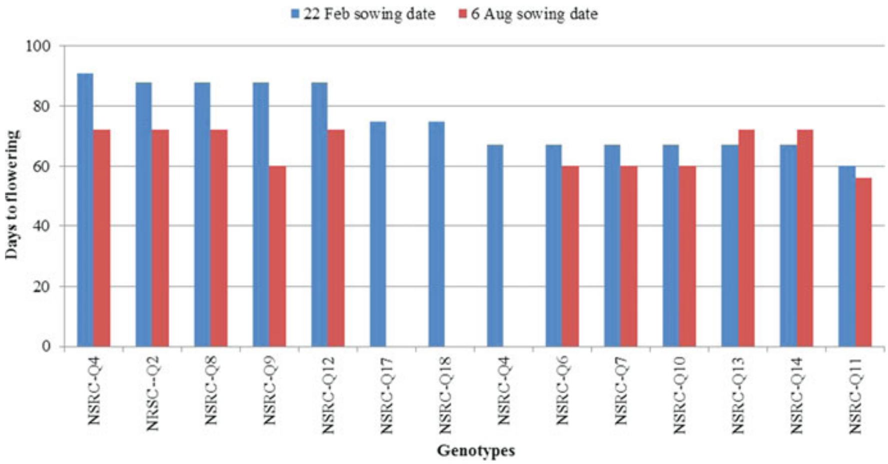


Fig. 3.9 Days to flowering of different quinoa genotypes at two sowing dates (February 22 and August 6)

In Aug sowing date 560 mm saline water (14–17 dS m^{-1}) was applied in Yazd. The amount of applied water and rainfall during growth period for this genotype was almost the same as Turkey, where 2.3 t ha^{-1} seed yield with 20 dS m^{-1} saline water was obtained (Yazar et al. 2015). In spring sowing date growing cycle prolong to 132 days and seed yield and weight were lower than Aug sowing date. Plant produced higher biomass but during seed filling period high temperature reduced seed yield. For Central Plateau of Iran the best sowing date is in the late of Aug. But sensitivity of the emergence stage is the main obstacle for this area because of shortage of fresh water.

The best sowing date for spring cropping was 24 Feb and the highest yield was observed at 22 Aug sowing date (Salehi 2017a). Genotypes evaluated in 24 Feb and 22 Aug sowing date and the highest seed yield was observed at Aug sowing date with 3.2 t ha^{-1} under saline water (14 dS m^{-1}) irrigation. Max Seed yield in Feb sowing date was 1.6 t ha^{-1}. Main problems of Feb sowing date was heat stress and in Aug sowing date low temperature during grain filling period. Then early mature genotypes are successful in both sowing date but genotypes had different response to photoperiod and heat stress. NSRC-Q9 and NSRC-Q10 in February in comparison to August sowing date started anthesis 28 and 7 days later, respectively (Fig. 3.9). Genotypes with high differences for time to anthesis in two sowing dates have high sensitivity to photoperiod. In spring cropping, successful genotypes have lower sensitivity to photoperiod and higher heat stress during grain filling. NSRC-Q6 and NSRC-Q10 had lower sensitivity to photoperiod, but NSRC-Q10 produced higher seed yield (Fig. 3.10). In general, NSRCQ9 and NSRCQ 10 were the best genotypes in August sowing date, and NSRC-Q6 was the best in February sowing date (Salehi 2017c).

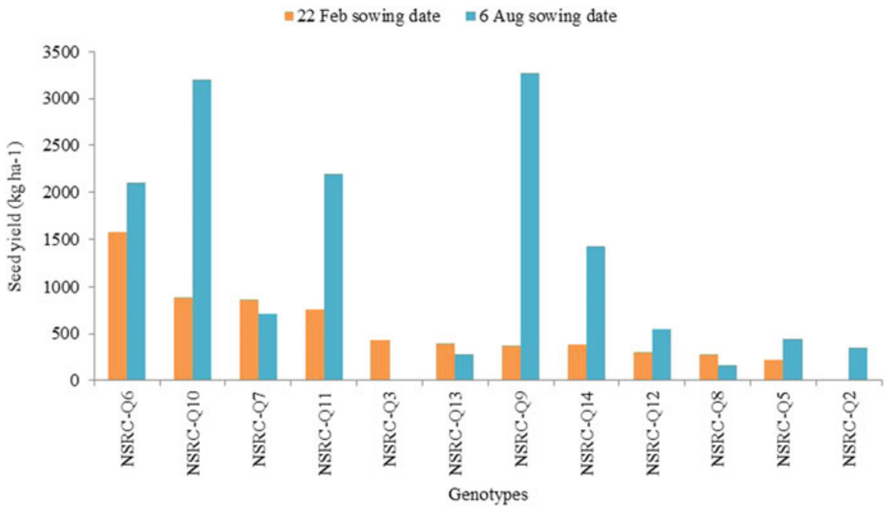


Fig. 3.10 Seed yield (kg ha^{-1}) of quinoa genotypes at two sowing dates (February 22 and August 6) irrigated with saline water (14 dS m^{-1})

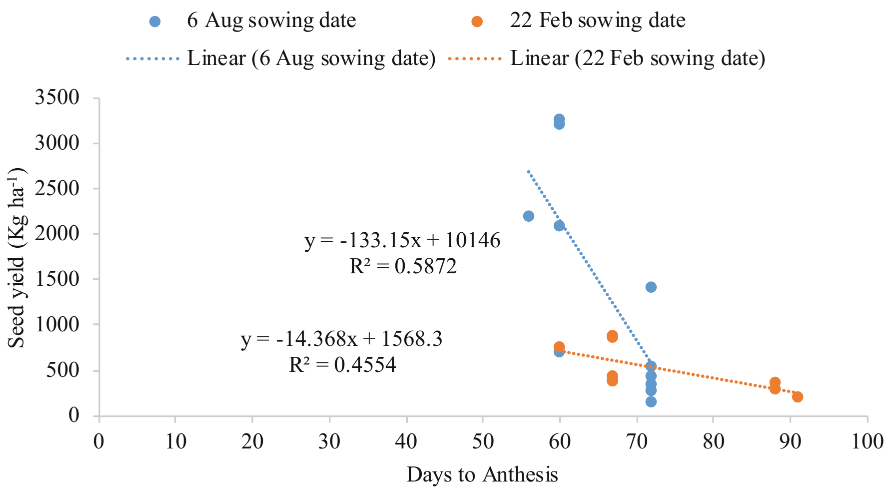


Fig. 3.11 Effect of day to anthesis on seed yield (kg ha^{-1}) at two sowing dates

Delay time to flowering reduced seed yield in August sowing date with more intensity than February sowing date (Fig. 3.11). This result also confirmed the previous results and showed that seed filling period is more sensitive to low temperature. In February and August sowing date, seed yield reduced 14 and 133 kg ha^{-1} per 1 day delay time to anthesis. In February sowing date, NSRC-Q6 did not consider for regression fit because of high heat stress of the genotypes (Salehi 2017c).

3.2.2 Salicornia *spp.*

Among halophyte species, *Salicornia* is considered for development of coastal area in the north and south of Iran because of high seed production with seawater and extractable oil. *Salicornia* species and pattern in Iran showed that Iranian *Salicornia* species are different from *S. europea* and *S. bigelovii* and native species described by (Akhani 2003) as *Salicornia persica*. This species is tetraploid and native to central (Esfahan, Yazd, and Fars) of Iran (Fig. 3.12). Akhani (2003) introduced *S. persica* as new crop; it could produce high biomass and is normally grazed by goats and camel (Fig. 3.13). Akhani (2008) illustrated six species of *Salicornia* in central and south of Iran. Golestan and Urmia accessions in the north of Iran are different from central and south species (Fig. 3.14). Because of diversity of Iranian *Salicornia* and adaptation to different agroclimate conditions, it would be necessary to evaluate morphologic and phenologic characteristics and seed and biomass production.

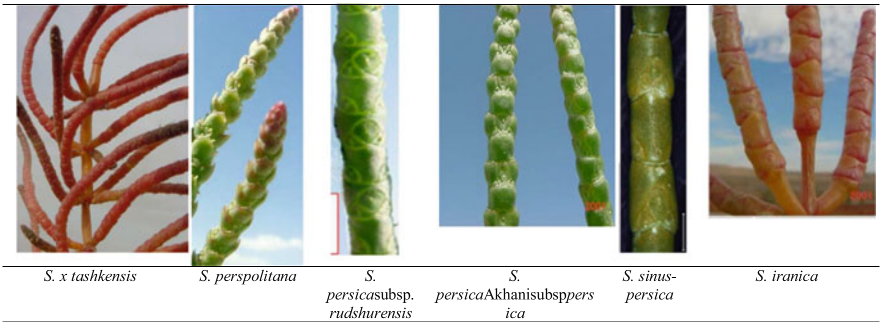


Fig. 3.12 Diversity among *Salicornia* species in Iran (Akhani 2008)

Fig. 3.13 Camel grazing from *Salicornia* after ripening during winter

Fig. 3.14 *Salicornia* habitat in the north of Iran by the Caspian Sea

Salicornia seeds of eight species (Fig. 3.15), four native and four exotic species, were sowed in Yazd in Central Plateau of Iran (54.2 E, 32.05 N). Soil texture of the field was sandy loam, and climate condition was arid with hot summer (44 °C max temperature) and cool winter (−6 °C min temperature) with 50 mm rainfall. Irrigation water was from groundwater with salinity of 14–17 dS m^{-1}.

In order to evaluate seed germination response to salinity, eight *Salicornia* species (*Salicornia sinus-persica*, *Salicornia persica*, Urmia and Golestan accessions and exotic accessions *S. europaea* and *S. bigelovii*) with eight levels of salinity (0, 100, 200, 300, 400, 500, 600, and 700 mM NaCl) evaluated under lab condition. All native *Salicornia* and *S. europaea* had more salt tolerance during germination stage than *S. bigelovii* (Fig. 3.16). At 700 mM salinity germination percent of *S. persica* and Golestan accession reduced 11–12%, and *S. europaea*, *S. sinus-persica* and Urmia accession reduced 26–39% but *S. bigelovii* germination reduced 72–87%. The germination percent of *S. bigelovii* reduced after increasing salinity above 100 mM. In *S. europaea* and *S. sinus-persica* accession germination percent reduced after 200 mM and in other accessions germination percent reduced after 300 mM. Among evaluated accessions *S. bigelovii-china* accession at germination stage was very sensitive to salinity in comparison to other accessions.

Cluster analysis of species at salinity above 400 mM showed that native *Salicornia* and *S. europaea* were more tolerant than *S. bigelovii*. At 700 mM salinity more than 70% of native *Salicornia* species seeds germinated, but just 17% of *S. bigelovii* germinated. Results showed that there is diversity among species for germination under saline condition, and the highest germination was recorded at salinity below 100 mM. Both halophytes and glycophytes response are similar to increase salinity stress; with both reduction in the initiation of germination and delay in the initiation of germination process (Ungar 1982).

Germination rate of all genotypes except S. bigelovii-china accession was the highest under nonsaline condition. At 700 mM salinity germination rate of *S. persica*

Salicornia speices	*S.sinus persica*	*S.bigelovii-Chian*	*S.bigelovii-red*	*S. european*	*Golestan*	*S.persica*	*Urmia*	*S.bigelovii*
Origin	South of Iran	China	Seperated from *S. bigelovii*	China	North of Iran by the Caspain sea	Central pleatue of Iran	North west of Iran by the Urima lake	Mexico

Fig. 3.15 *Salicornia* species and their origin which are sowed in the experiment

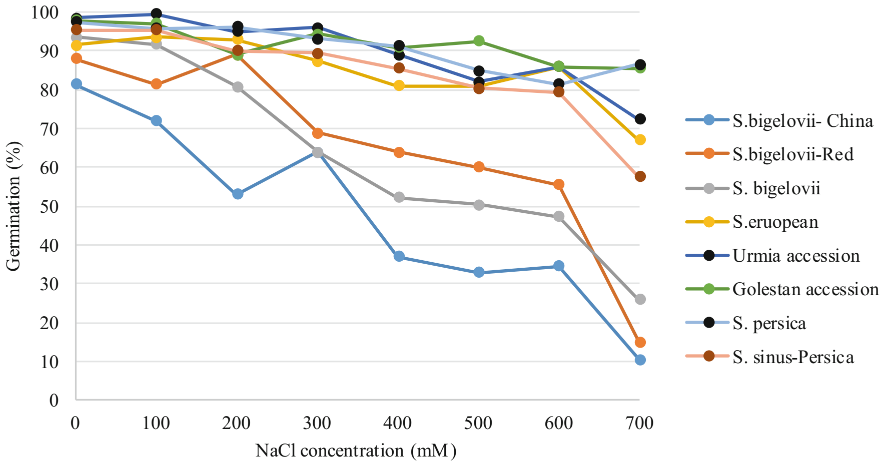


Fig. 3.16 Germination percentage of eight *Salicornia* species under NaCl stress (mM)

and Golestan accession was higher than other genotypes and achieved the peak after 7 days, but the lowest germination was observed in *S. bigelovii* and continues germination up to 15 days (Fig. 3.17)

Germination percentage of produced seeds under field condition and collected (from natural habitat) seeds of three species was evaluated. Under nonsaline condition, germination of produced seeds of Urmia and Golestan species was higher than collected seeds. At 600 mM salinity produced, seed salinity tolerance was higher than collected seeds (Fig. 3.18). In *S. sinus-persica*, Golestan and Urmia accessions germination of produced seeds under field condition were 70, 55 and 80% higher than collected seeds from natural habitat at 600 mM salinity, respectively.

In the south of Iran, seawater salinity range is 45–65 dS m^{-1}, and emergence of some species is low, then transplanting method examined for field evaluation of *Salicornia* species. Four seeds were sowed in each home of seedling tray, and seedlings were transplanted with 50 cm between row interval and 20 cm between plants on the row. In 1 ha for having 400,000 plants, 100,000 seedlings should be sown, and this method reduced the labor cost (Fig. 3.19). For producing transplant 2 weeks after emergence, fertilizer is applied twice a week (20–20–20 and microelement), and after 40 days the transplant is ready for sowing in the field. After transplanting, irrigation with saline was applied every 3–5 days interval for maintain soil moisture in field capacity. Thirty days after sowing, fertilizer is applied (ammonium nitrate) every 2 weeks with rate of 50 kg ha^{-1} (Salehi et al. 2017a). The main problem of native species of *Salicornia* was sensitivity to photoperiod. Ventura et al. (2011) reported that the best photoperiod for preventing flowering is 15-h day length. Based on flowering time, *S. persica* and *S. sinus-persica* flowered when the day length was 13.5 and 12.6 h, respectively, and other genotypes flowered when the day length was 14.3 h. Flowering of *S. persica* and *S. sinus-persica* was observed in greenhouse when the day length was 12 h. In *S. persica* and *S. sinus-persica*, day length longer than 13.5 and 12 h prevent flowering, respectively. Evaluation of

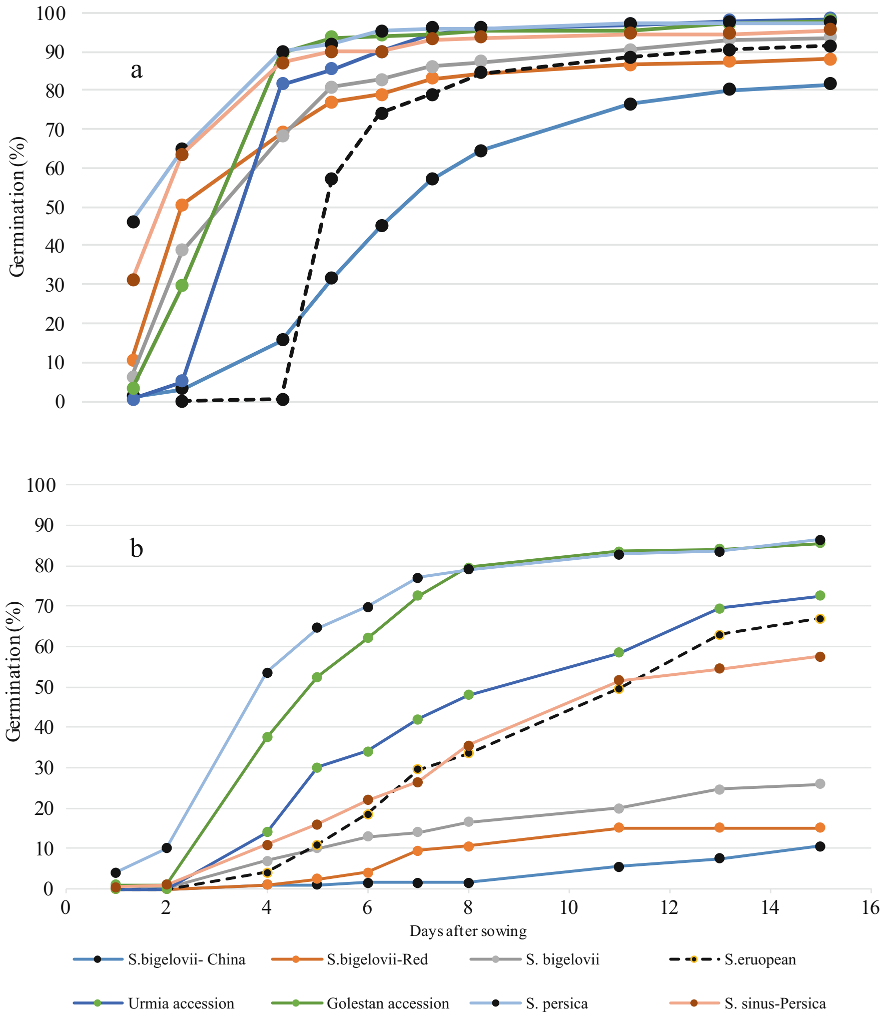


Fig. 3.17 Germination trend from sowing up to 15 days under nonsaline (**a**) and 700 mM NaCl condition (**b**)

photoperiod on flowering time of these two species is necessary. Another problem was pest, the main pest of *Salicornia* was termite, and it starts feeding on the stem when the stem is woody (Fig. 3.20).

The highest shoot fresh weight was observed at *S. bigelovii* with 7.8–8.3 kg per transplant 155 days after sowing (Fig. 3.21), and shoot dry weight was 1.6 kg per transplant. With 100,000 transplant per ha, shoot biomass production was 160 t ha^{-1}. After that *S. persica* produced 120 t ha^{-1} dry biomass, and the lowest biomass was observed in Urmia and *S. europaea* accessions with 69 and 72 t ha^{-1} (Table 3.2). The highest plant height was observed in *S. persica* and *S. sinus-persica* with 77–78 cm, and other species had 43–56 cm plant height. Shahid et al. (2013) reported that plant height of different species of *Salicornia* was between 49 and

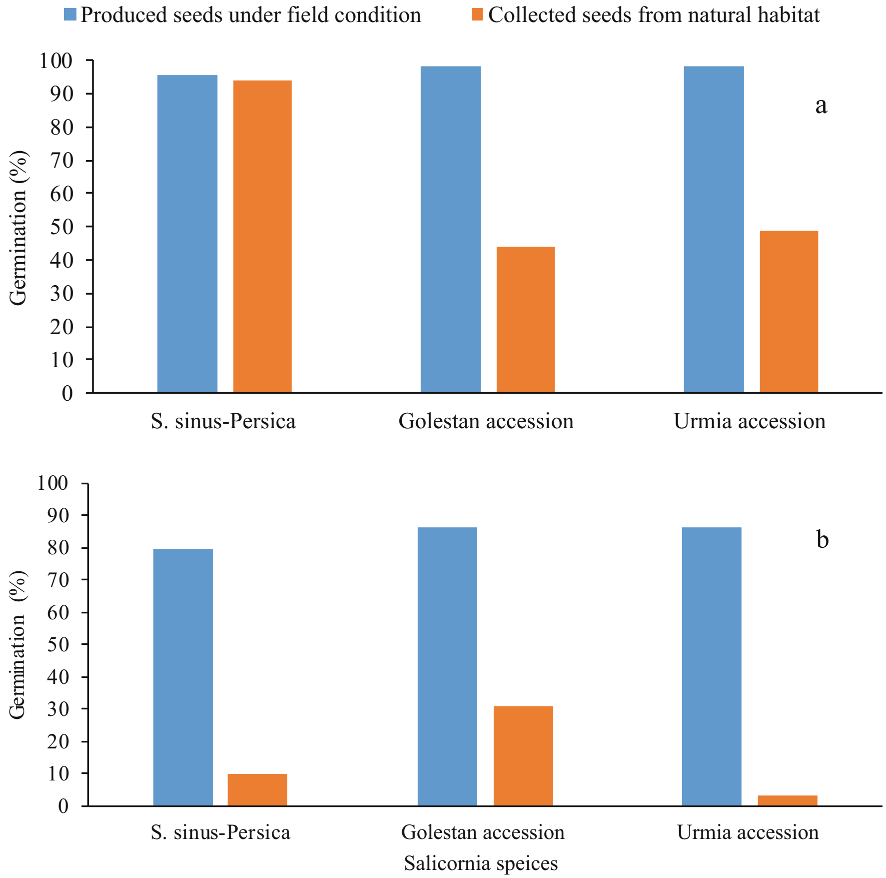


Fig. 3.18 Germination percentage of produced seeds under field condition and collected seed from natural habitat under nonsaline (**a**) and 600 mM NaCl (**b**)

63 cm. Among *S. bigelovii*, the red one had the highest plant height (54 cm). The highest seed yield was observed at red *S. bigelovii* with 3.6 t ha^{-1} and after that at *S. bigelovii* and *S. europaea* with 2.8 and 2.2 t ha^{-1}, respectively, and the lowest was observed in Urmia accession with 0.57 t ha^{-1}. Seed yield of *Salicornia* in Eritrea was reported 1.39–2.46 t ha^{-1} (Glenn et al. 1991; Glenn et al. 2013). The highest seed weight was observed in *S. bigelovii* after that in *S. europaea* with 1.06 and 0.79 mg, and the lowest was observed in Urmia and S. *sinus-persica* with 0.34 and 0.39 mg. The longest duration of day to flowering was observed at *S. sinus-persica* with 213 days after sowing and *S. persica* with 175 days, but other species started flowering at the same time (159 days). The main reason of lower seed yield of *S. sinus-persica* was low temperature during anthesis and despite of longer vegetative growth cycle could not produce high biomass.

Correlation among measured traits showed that seed production had significant correlation with spike diameter ($r = 0.81$), spike length ($r = 0.69$), spike weight

Fig. 3.19 Field trail of different *Salicornia* species irrigated with saline water which is irrigated by field technician (14–17 dS m^{-1}) (135 days after transplanting)

Fig. 3.20 Termite, main pest of *Salicornia*

Fig. 3.21 Performance of each transplant which is held by the field technician at 155 days after transplanting

($r = 0.86$), and 1000 seed weight ($r = 0.94$). Selection of plant based on spike diameter, weight, and length will improve seed yield and 1000 seed weight. Spike number had negative and significant correlation with seed production (Table 3.3). Golestan and Urmia produced significantly higher spike number, but seed production and 1000 seed weight were the lowest. Lyra et al. (2016) reported that all spike characteristics are correlated with seed yield, and they could be used in breeding programs.

Principal component analysis showed that spike dry weight, 1000 seed weight, and spike diameter had a positive and same direction, and the second component includes plant height and shoot fresh weight. On the first component, spike number per plant had high negative direction (Fig. 3.22). Lyra et al. (2016) reported that spike number highly and negatively correlated with seed yield.

Cluster analysis based on spike characteristics and seed weight per plant separated *S. bigelovii* red because of the highest seed number per spike, seed yield, spike diameter, spike weight, and the lowest spike number. Golestan and Urmia accessions with the highest spike number and lowest spike weight, spike length, spike diameter and seed number per spike. *S. persica* and *S. sinus-persica* were in same group, and *S. europaea*, *S. bigelovii-China*, and *S. bigelovii* were in the same group (Fig. 3.23). The highest oil percent was in *S. bigelovii* with 22% oil and after that in *S. persica* with 18% oil content (Fig. 3.24). Among the native *Salicornia*, *S. persica* had the highest oil content (Salehi 2017b). Oil content of *S. bigelovii* was reported 26–33% with 30–33% protein (O'Leary et al. 1985; Glenn et al. 2013).

3.3 Halophytes as Forage

Forage production of rangelands is estimated around 10.7 million tons per year, and fodder crops are mainly *Alfalfa*, clover, and maize with a production rate of 18.44 million tons in 2012 (Ahmadi et al. 2014). Each animal unit uses 511 kg of forage per year. Hence, 56.2 million tons of forage products are required for animal feed in Iran. The total forage production of the country (rangelands and forage in agriculture systems) is 29.1 million tons annually, and this is almost half of the forage requirement. Therefore, the remaining amount of forage requirement should be imported or provided by overgrazing in rangelands which causes excessive pressure on them. High water requirement of forage crops, low water quality, and sensitivity of current forage crops to salinity and water stress restrict their extension. At the same time, a large quantity of saline lands and saline water resources is available which could be allocated to the production of forage by halophyte farming.

Table 3.3 Pearson correlation among measured traits of *Salicornia* species

	Shoot fresh weight	Shoot dry weight	Plant height	Spike length	Spike dry weight	No. Seed per spike	Spike diameter	Spike per plant	1000 seed weight	Seed yield
Shoot fresh weight	1									
Shoot dry weight	**0.91****	1								
Plant height	0.38^{ns}	0.03^{ns}	1							
Spike length	0.43^{ns}	0.34^{ns}	0.03^{ns}	1						
Spike dry weight	0.65^{ns}	0.64^{ns}	−0.06^{ns}	**0.91****	1					
No. seed per spike	0.27^{ns}	0.47^{ns}	−0.64^{ns}	0.59^{ns}	**0.76***	1				
Spike diameter	**0.69***	**0.74***	−0.08^{ns}	0.64^{ns}	**0.79****	0.54^{ns}	1			
Spike per plant	−0.54^{ns}	−0.53^{ns}	0.05^{ns}	−0.65^{ns}	**−0.75***	−0.49^{ns}	**−0.95****	1		
1000 seed weight	0.43^{ns}	0.66^{ns}	−0.46^{ns}	0.52^{ns}	**0.72***	**0.73***	**0.84****	**−0.74***	1	
Seed yield	0.44^{ns}	0.62^{ns}	−0.43^{ns}	**0.69***	**0.86****	**0.86****	**0.81****	**−0.75***	**0.94****	1

*,** and ns are significant at 1 and 5% and non-significant, respectively

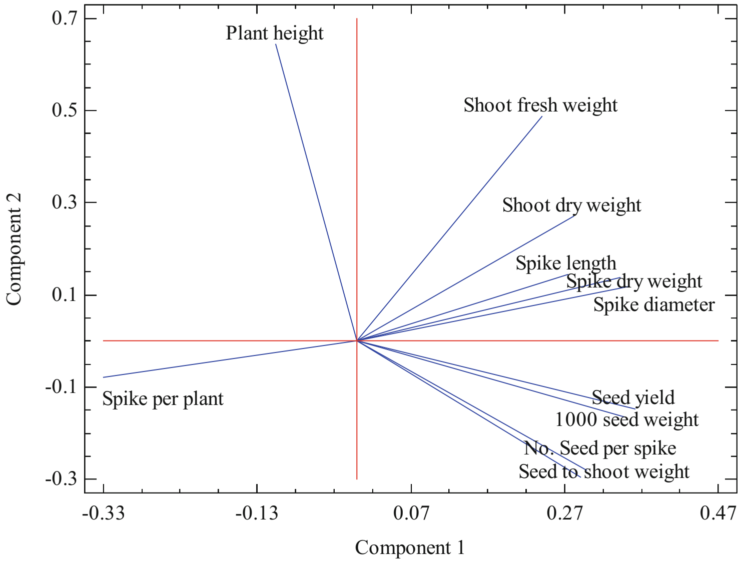
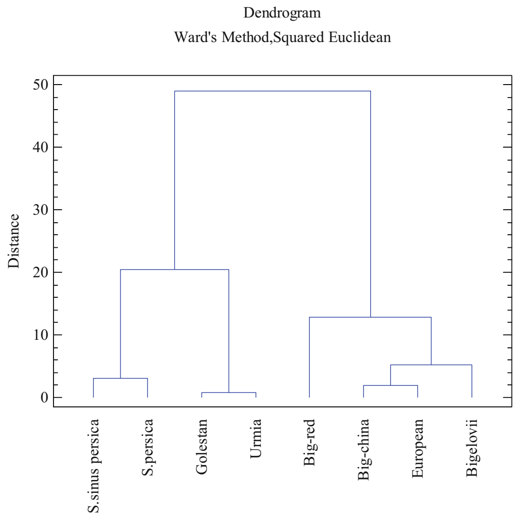


Fig. 3.22 Principle component analysis of measured traits of *Salicornia* under saline condition



Cluster	Spike length (cm)	Spike dry weight(g)	No. Seed per spike	Spike diameter(mm)	Spike per plant	1000 seed weight(mg)	Seed yield (g/transplant)
S.sinuspersica, S persica	12.28	1.46	157.23	4.458	6368	0.5	10.5
S.bigelovii red	14.85	3.39	341.63	5.43	2980	1.01	36.5
Urmia and Golestan accession	10.35	0.62	199.73	3.08	13924	0.39	6.28
S.bigelovii –china, S.european and S. bigelovii	12.01	1.68	247.96	5.07	3868.3	0.93	24.5

Fig. 3.23 Cluster analysis and measured traits' mean in each cluster

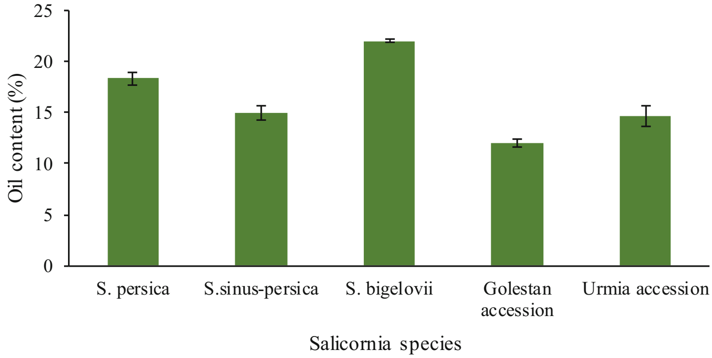


Fig. 3.24 Oil content (%) of different species of *Salicornia*

3.3.1 Kochia scoparia

Kochia is from Chenopodiaceae family, diploid, and annual crop and because of deep root system adapted with arid condition. *Kochia* is a pioneer crop in arid and semiarid condition. Different accessions of *Kochia* were found in Iran (Birjand, Borujerd, Sabzevar, Isfahan, and Urmia). Seed germination will reduced at pH lower than 2 or higher than 12. Like other crops, *Kochia* needs moisture for germination; seed germination is higher when sowing seed on the soil surface (74%) in comparison with sowing at 3 mm soil depth (54%). *Kochia* seeds establishment are successful with spring rainfall when mean air temperature is 5–10 °C. Seeds could germinate in wide temperature ranges (base, optimum, and ceiling temperature are 3.4, 25, and 43.7 °C) (Sabori et al. 2011). Evaluation of saline water effect on *Kochia* showed that when plant height is around 10 cm, saline water effect on plant growth is low (Salehi and Kafi 2011), but seed could germinate in high saline condition (Fig. 3.25).

Kochia is a short-day plant and starts flowering when day length is around 13–15 h (Bell et al. 1972). Based on climate condition and sowing date, *Kochia* could produce 2–3 cut a year. In Saskatchewan of Canada, *Kochia* produce 4.5–9 t ha^{-1} at 14 dS m^{-1} salinity (Steppuhn and Wall 1993). In Dakota and New Mexico kochia could produce 27.7 t ha^{-1} and 25 t ha^{-1}, respectively (Foster 1980). *Kochia* in semiarid condition of Iran produce 10 and 23 t DM ha^{-1} in summer and spring cropping, respectively, by 28 dS m^{-1} saline water (Salehi et al. 2013, 2010a, 2012a) (Table 3.4). In Mashhad (northeast of Iran), *Kochia* produce 7 t DM ha^{-1} with 21 dS m^{-1} saline water (Kafi et al. 2010). In arid condition of Central Plateau of Iran (Birjand), *Kochia* produce 6 t DM ha^{-1} with 28 dS m^{-1} saline water (Jami Al-Ahmad and Kafi 2008) (Table 3.4). *Kochia* could survival with gradual increasing of soil salinity up to 128 dS m^{-1} NaCl (Nabati et al. 2015). In summer and spring cropping, 1 mm increasing water application increased 6.7 and 4.8 kg ha^{-1} biomass

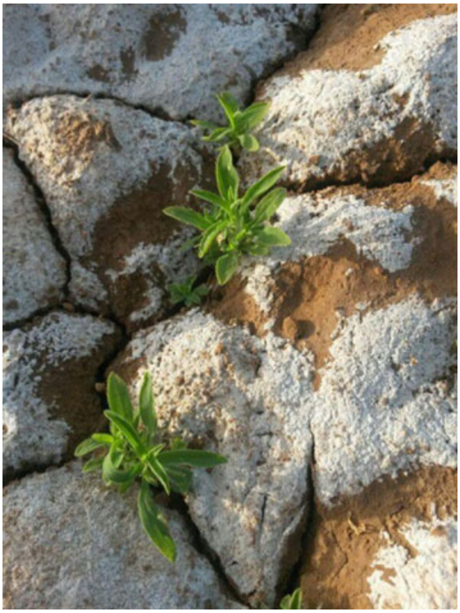


Fig. 3.25 *Kochia* emergence in 100 dS m^{-1} of ECe (Yazd-Iran)

Table 3.4 Biomass production of *Kochia* in different climate conditions and water salinity in Iran

	Shoot dry weight (kg ha^{-1})			
	Golestan (Salehi et al. 2012a, b)			
Saline water (dS m^{-1})	Summer cropping	Spring cropping	Mashhad (Kafi et al. 2010) Summer cropping	Birjand (Jami Al Ahmadi and Kafi 2008)
1.5	13.42	37.23	–	9.67
7	13.93	28.91	8.54	9.91
14	11.93	29.24	8.30	–
21	10.13	25.22	7.53	–
28	10.17	23.73	–	6.18
35	8.83	18.50	–	–
42	–	8.97	–	–

production, and increasing 1 dS m^{-1} water salinity in spring and summer cropping decreased 154 and 511 kg ha^{-1} biomass production (Salehi et al. 2012b).

Kochia forage yield and protein content improved by applying of nitrogen. Applying to much nitrogen led to nitrate and oxalate accumulation. *Kochia* needs 50 kg ha^{-1} nitrogen and 20 kg ha^{-1} P_2O_5 (Coxworth et al. 1988; Khani-nejad et al. 2013). Leaves' color change is the main symptom of nitrogen deficiency.

Cohen et al. (1989) and Mir et al. (1987) reported that combination of *Kochia* more than 50% of the diet of beef cattle and sheep severely reduced intake. Harvesting stage has a large effect on the nutritive value and intake of *Kochia*. Nutritive value and intake of *Kochia* at or before full bloom stage are similar to

Fig. 3.26 *Kochia* before bloom stage

Alfalfa (Knipfel et al. 1989) (Fig. 3.26). *Kochia* accumulated large amounts of minerals (K, Na, Ca, and Mg) especially when grown under saline condition (Salehi et al. 2011; Green et al. 1986). Almost all halophytes cause mineral imbalance in animals (Norman et al. 2013).

There are successful experiences of *Kochia* growing around the world. In Japan *Kochia* grow as ornamental plant (Fig. 3.27a), in Iran, Canada, and Mexico grow kochia as forage (Fig. 3.27). Farmers in Alberta, Canada, grew and fed *Kochia* to cattle for more than 50 years, and they know not to feed cattle more than 50% in the diet. In Iran in Khorasan and Lorestan provinces, they grow *Kochia* (Fig. 3.27b and d) mostly for making broom. In Khorasan they grow *Kochia* in mix cropping with cotton and sugarbeet (Fig. 3.27d), and area under cultivation in Khorasan is almost 40 ha, and forage production is 40–60 t ha^{-1}.

Kochia is resistant to pest and grasshopper. There is not a report on pest and diseases of *Kochia*. In Golestan provinces of Iran, high population of *Bulaea lichatschovi* was observed (Fig. 3.28). These species feed on pollen of Chenopodiaceae family (Iablokoff-Khnzorian 1982).

Biofuel production has been encouraged over the past years as a potential alternative to partially meet expected future energy demands and reduce the negative impact of fossil fuels on greenhouse gas emissions. Corn stoffer, wheat straw, and *Alfalfa* forage have potential as bioenergy feedstocks for ethanol production, but corn and wheat have considerable input requirements, and all three types of biomass are heavily used for animal feed in developing countries. Halophytes which produce biomass with saline irrigation water or on sodic soils may be an important alternative for growing biofuel feedstocks on saline (marginal) lands that are unfit for food crop

Fig. 3.27 Sowing *Kochia* for different purposes: Ornamental (Japan) (**a**), broom and forage (Iran) (**b** and **d**), and mix cropping (**c**). (Photo **b** and **c** from Dr. Hasheminegad)

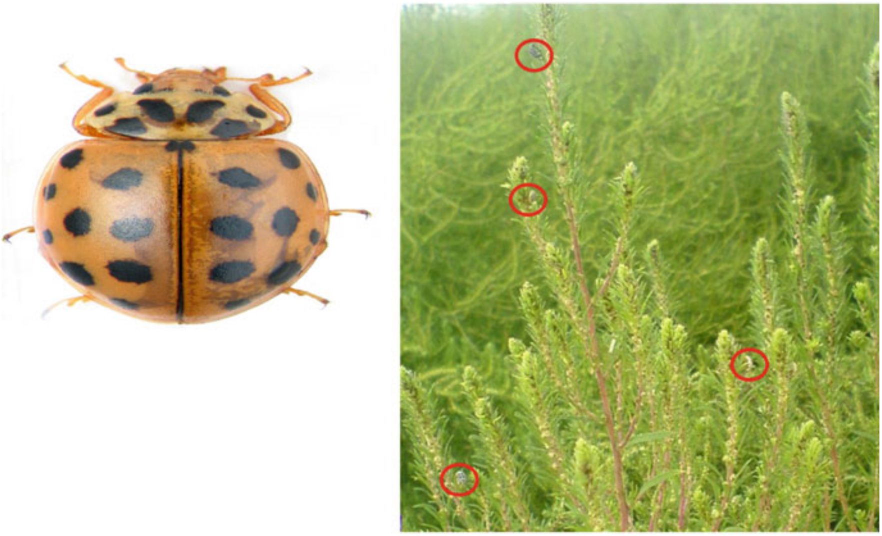


Fig. 3.28 High population of *Bulaea lichatschovi* on *Kochia*

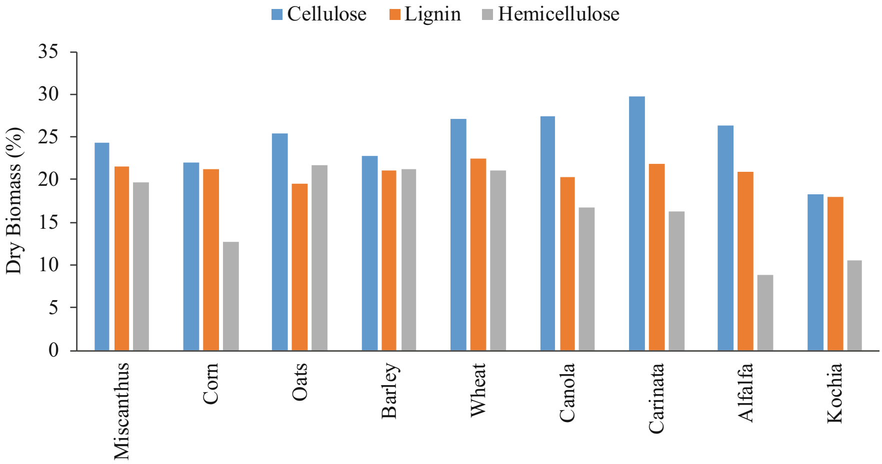


Fig. 3.29 Cellulose, lignin, and hemicellulose content of *Kochia* biomass in comparison with other crop residues. Data represents the means of three replicate biomass samples

cultivation. *Kochia* provides an option to farmers to cultivate a high-biomass, salt-tolerant lignocellulosic species that can be grown without intruding of fresh water and agriculture land resources and can be used for either forage or bioethanol production. Cellulose content was most similar but somewhat lower in *Kochia* than corn stoffer, but overall, *Kochia* biomass had lower cellulose, hemicellulose, and lignin content than the other biofeedstocks. Glucose was the main sugar in *Kochia*, followed by xylose, but both sugars were twofold lower than that of other biofuel feedstock species (Fig. 3.29). With the exception of furfural, inhibitors and phenolic concentrations in *Kochia* are not sufficiently high to inhibit fermentation processes (Kafi et al. 2014). Improvements in agronomy, genetics, and bioconversion factors will help *Kochia* biomass production and the development of a biofuel industry that uses *Kochia* (Salehi et al. 2010b).

3.3.2 Panicum antidotale

The Poaceae includes over 7500 species and shows a wide range of salinity tolerance. In *Bouteloua* and *Distichlis* and *S. virginicus*, 50% of growth reduction ranged from 150 mM to more than 600 mM, respectively (Marcum 2008). *Panicum antidotale* is grass and can grow under a wide range of climate condition (Fig. 3.30). *Panicum* is a native plant of Indo-Pakistan and growing in a variety of soils. *Panicum* came to Iran in 1960 from India for sand dune establishment in Khuzestan, and the results were remarkable. In 1984, ten million *Panicum* and *Cenchrus ciliaris* seedlings were sown in sand dunes of Allahabad, Ahvaz (southwest), with hot climate condition. In 1974 *Panicum* was sown in Sabzevar (Northeast) with different climate conditions (semiarid and cold climate), and results were promising. This

Fig. 3.30 *Panicum* production with saline water (14–17 dS m^{-1}) Yazd, Iran

plant can grow under arid and semiarid condition and produce 150–180 t Fw ha^{-1} annually with protein content of 15–18% (Bokhari et al. 1987). Protein content of forage from sand dunes of Khuzestan was 11.1% and most palatable during vegetative until flowering stage (Hoveize et al. 2006). Although *Panicum* could produce acceptable biomass during 3–4 years, after this period forage production and plant size were reduced. Hoveize et al. (2006) showed that 18 days cutting interval improves production and bud formation of *Panicum* in Khuzestan (Hoveize et al. 2006). The best method of sowing in Sabzevar (with 204 mm rainfall) was sowing seedling with pots in this method *Panicum* produce 523 kg DM ha^{-1}, and the best sowing time was April 4 under rainfed condition (Ahmadi Yazdi et al. 1985). Banch Shafiei and Eslami (2000) evaluated superabsorbent polymer on *Panicum* production in three soil types, and results showed that absorbent improves *Panicum* production in light texture soil. Banakar et al.'s (2015) results on effect of density on *Panicum* production showed that 10 kg of seed or 4 t ha^{-1} rhizome should apply for sowing. Hoveize et al. (2006) mentioned that nitrogen fertilizer and grazing are essential for survival of *Panicum* in sand dunes; after each cut 50 kg ha^{-1} urea should be applied.

This plant has high tolerance to salinity, drought, fire, and water logging condition (Ashraf 2003). Selection of clone with high salt tolerance and biomass makes an opportunity for the farmers to grow it as forage crop (Ashraf 2003). *Panicum* could produce 17 t DM ha^{-1} biomass under nonsaline condition and at 16 dS m^{-1} could produce 10 t DM ha^{-1}, and 50% of forage production occurred at 20 dS m^{-1} (Fig. 3.31) (Banakar et al. 2015; Eshghizadeh et al. 2012). *Panicum* forage contains 18.8% protein, 40% crude protein, and 7.9% ash (Hameed and Ashraf 2008). Tavakoli et al. (2008) evaluated *Atriplex canescens* and *Panicum antidotale* forage ratio on sheep diet and showed that 75% *Atriplex* and 25% *Panicum* improved dry matter digestibility and crude protein of sheep diet in comparison to use individual

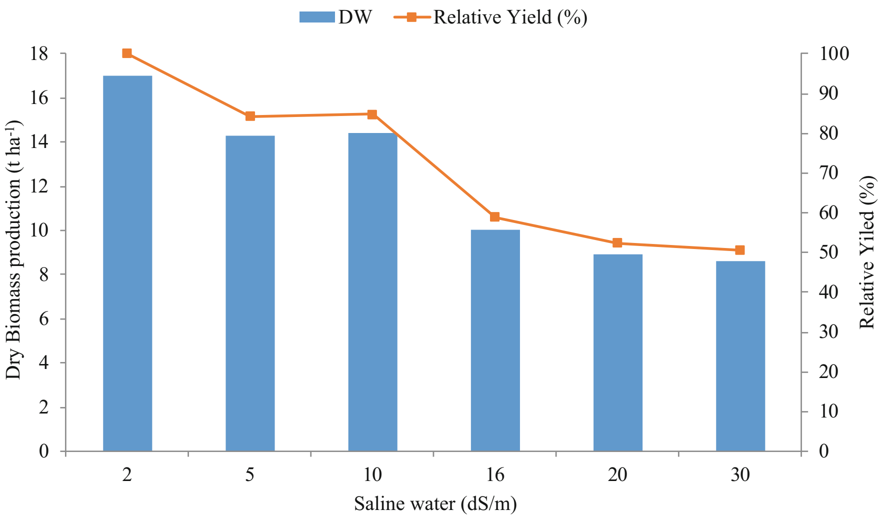


Fig. 3.31 Dry matter production (t ha^{-1}) and relative yield (%) of *Panicum* under different irrigation water salinities

crop. Bitaraf et al. (2015) evaluated (100:0, 75:25, 50:50, and 75:25%) ratio of *Alfalfa* and *Panicum* on ruminants' diet, and they showed that the best ratio for using *Panicum* in ruminants' diet is 25%.

Hameed and Ashraf (2008) showed that under saline condition (200 mM NaCl), the population from saline soil produced higher fresh and dry biomass of shoot and root than population from nonsaline condition. Because of the high variation among *Panicum* population, clone selection was used for improvement of *Panicum* population (Salehi et al. 2015). *Panicum* has hermaphrodite flowers, and cross pollination is by wind, and propagation is done by seed and rhizome (Shahbaz et al. 2011). Two thousand plants were sown with 50 cm interval and evaluated for better performance under saline soil and water and based on visual performance of 240 plants selected for evaluating biomass production. At the 2nd year, rhizomes of 100 clones were sown in a line without replication, and biomass production was evaluated. There was high diversity among clones, and 4 and 33% of clone produce 853 and 224 g m^{-2} dry biomass (Fig. 3.32). Water requirement of *Panicum* is half of *Alfalfa* (Bokhari et al. 1987), and a salt-tolerant population had higher water use efficiency as compared to a normal population under saline condition (Hameed and Ashraf 2008). Twenty four selected clones were evaluated in the replicated experiment in the soil with 80 dS m^{-1} salinity and 15–17 dS m^{-1} saline water. Results showed that the highest biomass production obtained at third cut and four clones produced significantly higher biomass. The procedure of clonal selection was shown in Fig. 3.33 (Farsi and Bagheri 2002).

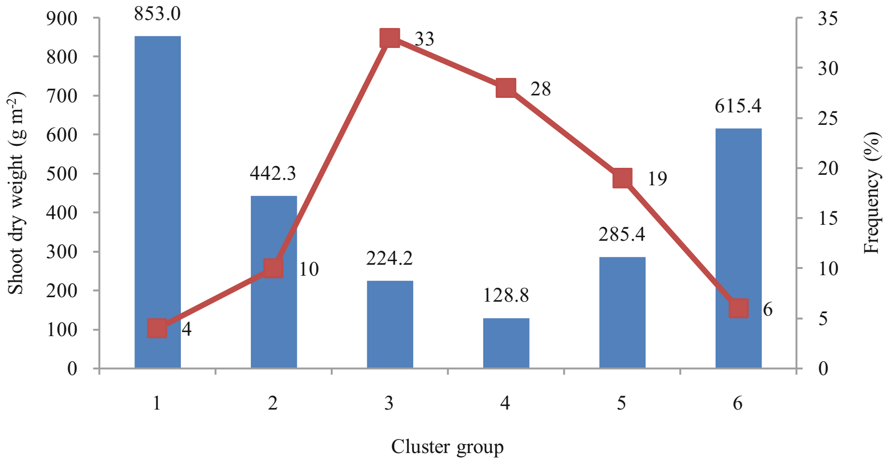


Fig. 3.32 Shoot biomass production (g m^{-2}) and frequency (%) of 100 *Panicum* clones under saline condition (15–17 dS m^{-1})

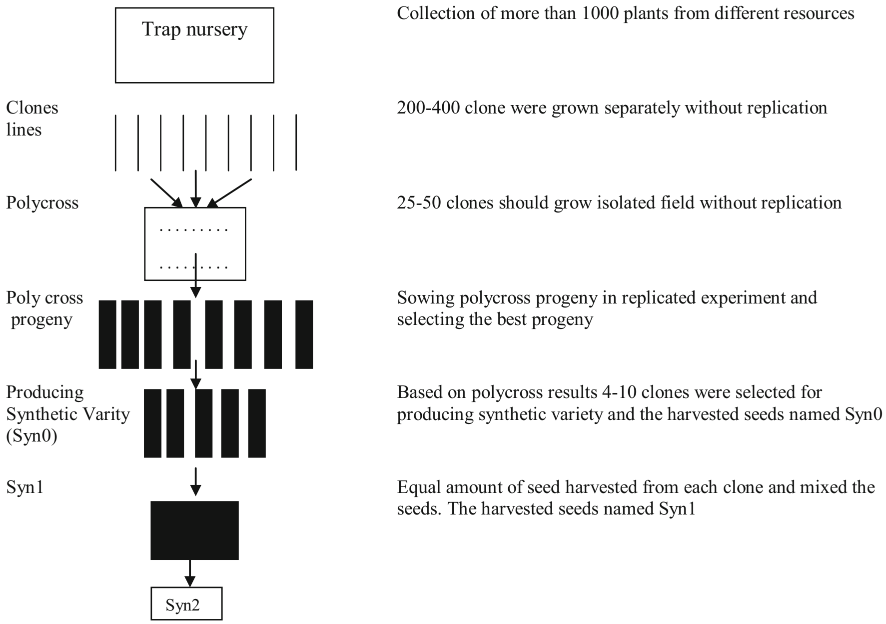


Fig. 3.33 Process of producing synthetic seeds of *Panicum antidotale*

3.4 Conclusion

Among evaluated halophytes, quinoa was considered for high nutritional quality. The emergence of seed is sensitive to salinity, and then in saline areas, farmers don't have fresh water, and quinoa is sensitive to saline water during emergence and early establishment. It would be better with increasing salinity above 7 dS/m that farmers apply more seed in sowing time. Quinoa had a short-day quantitative response to photoperiod and photoperiod longer than 12-h prolonged time to flowering. Among the sowing dates, August 22 was selected because of shorter growing cycle and higher seed production. Among evaluated genotypes in two sowing dates, there was a high diversity among genotypes for day length and heat stress response. Quinoa could produce 2–3 t ha^{-1} seed with 14 dS m^{-1} saline water. It could be considered as new crop for marginal land and saline water. Iran has three main agroclimate conditions for quinoa production. Central plateau with very warm summer and cool winter, where quinoa could be cultivated in the Aug up to mid-autumn; in the south of Iran with mild winter could be cultivated as winter crop and in the northern part of Iran with mild summer could be cultivated as spring crop. The Ministry of Agriculture together with National Salinity Research Center (NSRC) started training of the farmers to grow quinoa under saline condition and the results was promising. NSRC introduced four salt tolerance lines of quinoa with different commercial colour (red, white and black) for different agroclimate conditions. In 2019, the area under quinoa cultivation was 700 ha and the seed yield of the farmers was 0.5–5 t ha^{-1}. Three private companies have constructed quinoa seed processing and sorting machines. *Kochia scoparia* could be considered as forage and pioneer crop in high saline land. It could produce 25 t ha^{-1} dry matter with 21 dS m^{-1} saline water. *Kochia* forage could be fed to cows up to 50% in diet. *Panicum antidotale* is a perennial forage crop from Poaceae family. It could be applied 25% in ruminants' diet and produce 10 t ha^{-1} dry biomass with 16 dS m^{-1} saline water. Clonal selection was the best method for improvment of panicum under saline condition. Four selected clones produced high biomass with saline water and were selected for seed production. *Salicornia* species produced remarkable yield with 17 dS m^{-1} saline water. *Salicornia bigelovii* red accession could produce 3.6 t ha^{-1} seed yield with 22% oil content.

Fresh water scarcity and food import dependency threaten food security of Iran. Native and exotic species of halophytes which are reported in this chapter was very successful for using saline water resources for producing food and feed. NSRC demonstrated the value of saline water resources potential for improving food security, and the results could be used by farmers and other countries in the region. For crossing the bridge between research output and extension, NSRC starts working with farmers and private companies for quinoa production, processing, and marketing, haloculture for dust storm controlling in Khuzestan by using drainage water and coastal area development project by *Salicornia* farming.

References

Abugoch James LE (2009) Chapter 1 quinoa (*Chenopodium quinoa* Willd.): composition, chemistry, nutritional, and functional properties. In: Steve LT (ed) Advances in food and nutrition research. Academic, Amsterdam

Ahmadi Yazdi MJ, Zargar A, Rahbar S (1985) Survey the best method and date of dry farming of *Panicum antidotale* in Sabzevar region. Agricultural Research, Education and Extension Organization Research Institute of forests and Rangelands, Tehran, Iran

Ahmadi K, Gholizadeh H, Ebadzadeh HR, Hosseini Pour R, Hatami F, Fazli B, Kazemiyan A Rafiee M (2014) Agricultural statistics of Iran. Ministry of Agriculture

Ahmadi K, Gholi Zadeh H, Ebad Zadeh HR, Estabragh F, Hossein Pour V, Kazemiyan A. & Rafeei M (2015) Agriculture Statistics report of 2013 growing season. Jahad Keshavarzi

Akani H (2006) Biodiversity of halophytic and sabkha ecosystems in Iran. In: Khan MA, Boer B, Stanislavovich Kust G, Barth HJ (eds) Sabkha ecosystems volume II: West and Central Asia. Springer, Dordrecht

Akhani H (2003) Salicornia persica Akhani (Chenopodiaceae), a remarkable new species from Central Iran. Linzer Biol Beitr 35(1):607–612

Akhani H (2008) Taxonomic revision of the genus Salicornia L.(Chenopodiaceae) in Central and Southern Iran. Pak J Bot 40:1635–1655

Anwar F, Hussain AI, Ashraf M, Jamail A, Iqbal S (2006) Effect of salinity on yield and quality of Moringa oleifera seed oil. Grasas Aceites 57:394–401

Ashraf M (2003) Relationships between leaf gas exchange characteristics and growth of differently adapted populations of blue panicgrass (*Panicum antidotale* Retz.) under salinity or waterlogging. Plant Sci 165:69–75

Askari H, Edqvist J, Hajheidari M, Kafi M, Salekdeh GH (2006) Effects of salinity levels on proteome of *Suaeda aegyptiaca* leaves. Proteomics 6:2542–2554

Aslam Z, Jeschke W, Barrett-Lennard E, Setter T, Watkin E, Greenway H (1986) Effects of external NaCl on the growth of Atriplex amnicola and the ion relations and carbohydrate status of the leaves. Plant Cell Environ 9:571–580

Banakar MH, Cheraghi SAM, Hasheminegad Y, Fielekesh A, Anagholi A, Ghane F, Soltani V (2015) Determining the best planting density of *Panicum antidotale* for forage production under saline and non saline for forage production under saline and non saline condition with two planting method. Agricultural Research, Education and Extension Organization National Salinity Research Center, Tehran, Iran

Banch Shafiei S, Eslami E (2000) The effects of super absorbent polymer on water holding capacity of a sandy soil using different amount of Polymer. Agricultural Research, Education and Extension Organization Research Institute of forests and Rangelands, Tehran, Iran

Barrett-Lennard EG, Norman HC, Dixon K (2016) Improving saltland revegetation through understanding the "recruitment niche": potential lessons for ecological restoration in extreme environments. Restor Ecol 24:S91

Bazile D, Bertero H, Nieto C (2015) State of the art report on quinoa around the world in 2013. FAO, Rome

Bell AR, Nalewaja JD, Schooler AB (1972) Light period, temperature, and kochia flowering. Weed Sci 20:462–464

Bertero H, King R, Hall A (1999) Photoperiod-sensitive development phases in quinoa (*Chenopodium quinoa* Willd.). Field Crop Res 60:231–243

Bitaraf A, Banakar MH, Shokohmand M, Shafi Naderi A, Mofidi MR, Shiran M, Rezaei M, Mohammad Zadeh H (2015) Determining nutritive value of *Panicum antidotale*. Agricultural Research, Education and Extension Organization Animal Science Institute of Iran, Tehran

Bokhari U, Alyaeesh F, Al-Nori M (1987) Adaptive strategies of desert grasses in Saudi Arabia. J Range Manag 40:19–22

Brakez M, EL Brik K, Daoud S, Harrouni MC (2013) Performance of *Chenopodium quinoa* under salt stress. In: Developments in soil salinity assessment and reclamation. Springer, Dordrecht

Cheraghi SAM (2012) Status and new developments on the use of brackish water for agricultural production in the near East Iran country report. FAO, Rome

Cohen RDH, Iwaasa AD, Mann ME, Coxworth E, Kernan JA (1989) Studies on the feeding value of *Kochia scoparia* (L.) Schrad. Hay for beef cattle. Can J Anim Sci 69:735–743

Coxworth E, Green D, Kernan J (1988) Improving the agronomic and feed value of kochia. Saskatchewan research council, SRC technical report no. R-814-4-B-88

de Munter JS, Hu FB, Spiegelman D, Franz M, Van Dam RM (2007) Whole grain, bran, and germ intake and risk of type 2 diabetes: a prospective cohort study and systematic review. PLoS Med 4:e261

Debez A, Taamalli W, Saadaoui D, Ouerghi Z, Zarrouk M, Huchzermeyer B, Abdelly C (2006) Salt effect on growth, photosynthesis, seed yield and oil composition of the potential crop halophyte Cakile maritima. In: Biosaline Agriculture and Salinity Tolerance in Plants. Springer, Berlin

Dehghany F, Alayi Yazdi F, Malakouti MJ. 2003. Evaluation of irrigation water quality due to nutritional disorders in Yazd Province. Soil and Water Research Institute,

Eshghizadeh HR, Kafi M, Ahmad N (2012) The mechanisms of salinity tolerance in the xero-halophyte blue panicgrass (*Panicum antidotale* Retz). Notulae Scientia Biologicae 4:59–64

Farsi M, Bagheri A (2002) Principle of plant breeding, Mashhad-Iran, Jahad Daneshgahi of Mashhad

Flowers TJ, Colmer TD (2008) Salinity tolerance in halophytes. New Phytol 179:945–963

Foster C (1980) Kochia-poor man's alfalfa shows potential as feed. Rangeland 2:22–23

Garcia M, Condori B, Castillo CD (2015) Agroecological and agronomic cultural practices of quinoa in South America. In: Quinoa*:* Improvement and Sustainable Production. Wiley, Hoboken, pp 25–46

Glenn EP, O'leary JW, Watson MC, Thompson TL, Kuehl RO (1991) *Salicornia bigelovii* Torr.: an oilseed halophyte for seawater irrigation. Science 251:1065–1067

Glenn EP, Anday T, Chaturvedi R, Martinez-Garcia R, Pearlstein S, Soliz D, Nelson SG, Felger RS (2013) Three halophytes for saline-water agriculture: an oilseed, a forage and a grain crop. Environ Exp Bot 92:110–121

Gómez-Pando L, Álvarez-Castro R, Eguiluz DE, la Barra A (2010) Effect of salt stress on Peruvian germplasm of Chenopodium quinoa Willd.: a promising crop. J Agron Crop Sci 196:391–396

Green D, Knipfel J, Kernan J, Coxworth E (1986) Evaluation of Kochia as a high yielding forage crop for saline soils. Soil and crop workshop. University of Saskatchewan, Saskatoon

Greenway H (1968) Growth stimulation by high chloride concentrations in halophytes. Israel J Bot 17:169–177

Gul B, Ansari R, Flowers TJ, Khan MA (2013) Germination strategies of halophyte seeds under salinity. Environ Exp Bot 92:4–18

Gulzar S, Khan MA (2001) Seed germination of a halophytic grass *Aeluropus lagopoides*. Ann Bot 87:319–324

Hamed KB, Magné C, Abdelly C (2014) From halophyte research to halophytes farming. In: Sabkha ecosystems: Volume IV: Cash crop halophyte and biodiversity conservation. Springer, Dordrecht

Hameed M, Ashraf M (2008) *Panicum antidotale*: A potential grass for salt affected soils. In: Kafi M, Khan MA (eds) Crop and forage production using saline waters. NAM S and T Centre, Daya Publishing House, New Dehli

Hariadi Y, Marandon K, Tian Y, Jacobsen S-E, Shabala S (2011) Ionic and osmotic relations in quinoa (*Chenopodium quinoa* Willd.) plants grown at various salinity levels. J Exp Bot 62:185–193

Hoveize H, Dinarvand M, Hasonizadeh AK, Sanadgol A (2006) Response of blue panic grass (*Panicum antidotale*) to clipping frequency. Agricultural Research, Education and Extension Organization Research Institute of forests and Rangelands, Tehran, Iran

Iablokoff-Khnzorian SM (1982) Les Coccinelles (Coleopteres-Coccinellidae) [Les Coccinellini des Regions Palearctiqueet Orientale]. Soc. Nouvelle des editions Boubee, Paris

Jacobsen SE (2003) The worldwide potential for quinoa (*Chenopodium quinoa* Willd.). Food Rev Intl 19:167–177

Jacobsen SE, Mujica A, Jensen C (2003) The resistance of quinoa (*Chenopodium quinoa* Willd.) to adverse abiotic factors. Food Rev Intl 19:99–109

Jami Al-Ahmad M, Kafi M (2008) Kochia (*Kochia Scoparia L.*): to be or not to be. In: Kafi M, Khan MA (eds) Crop and forage production using saline waters. Springer, India

Jenkins S, Barrett-Lennard EG, Rengel Z (2010) Impacts of waterlogging and salinity on puccinellia (*Puccinellia ciliata*) and tall wheatgrass (*Thinopyrum ponticum*): zonation on saltland with a shallow water-table, plant growth, and Na+ and K+ concentrations in the leaves. Plant Soil 329:91–104

Kafi M, Asadi H, Ganjeali A (2010) Possible utilization of high-salinity waters and application of low amounts of water for production of the halophyte *Kochia scoparia* as alternative fodder in saline agroecosystems. Agric Water Manag 97:139–147

Kafi M, Gul B, Salehi M (2014) Kochia (*Kochia scoparia* (L.) Schrad) unwanted or wanted plant for forage production in harsh environments. In: *Sabkha Ecosystems: Volume IV: Cash Crop Halophyte and Biodiversity Conservation*. Springer, Dordrecht

Khan MA, Ungar IA, Showalter AM (2000) Effects of salinity on growth, water relations and ion accumulation of the subtropical perennial halophyte *Atriplex griffithii* var stocksii. Ann Botany 85:225–232

Khani-Nejad S, Kafi M, Khazai HR, Shabahang J, Nabati J (2013) Evaluation of nitrogen and phosphate on forage yield of kochia under irrigation with two water resources. Iraninan J Field Crop Res 11:275–282

Knipfel JE, Kernan JA, Coxworth EC, Cohen RDH (1989) The effect of stage of maturity on the nutritive value of kochia. Can J Anim Sci 69:1111–1114

Koyro H-W, Lieth H (2008) Global water crisis: the potential of cash crop halophytes to reduce the dilemma. In: *Mangroves and halophytes: restoration and utilisation*. Springer, Dordrecht, pp 7–19

Koyro HW, Lieth H, Eisa SS (2008) Salt tolerance of *Chenopodium quinoa* Willd., grains of the Andes: influence of salinity on biomass production, yield, composition of reserves in the seeds, water and solute relations. In: *Mangroves and Halophytes: Restoration and Utilisation*. Springer, Dordrecht, pp 133–145

Lavini A, Pulvento C, D'andria R, Riccardi M, Choukr-Allah R, Belhabib O, Incekaya Ç, Metin Sezen S, Qadir M, Jacobsen SE (2014) Quinoa's potential in the Mediterranean region. J Agron Crop Sci 200:344–360

Liu X, Duan D, Li W, Tadano T, Khan MA (2006) A comparative study on responses of growth and solute composition in halophytes Suaeda salsa and Limonium bicolor to salinity. In: Ecophysiology of high salinity tolerant plants. Springer, Dordrecht

Loftas T, Ross J (1995) Dimensions of need: an atlas of food and agriculture. Food & Agriculture Org, Rome

Lyra DA, Ismail S, Butt KURB, Brown J (2016) Evaluating the growth performance of eleven '*Salicornia bigelovii*' populations under full strength seawater irrigation using multivariate analyses. Aust J Crop Sci 10:1429

Madani K, Aghakouchak A, Mirchi A (2016) Iran's socio-economic drought: challenges of a water-bankrupt nation. Iran Stud 49:997–1016

Marcum KB (2008) Saline tolerance physiology in grasses. In: Ecophysiology of high salinity tolerant plants. Springer, Dordrecht

Mesgaran M, Madani K, Hashemi H, Azadi P (2016) Evaluation of land and precipitation for agriculture in Iran. Working Paper 2, Stanford Iran 2040 Project, Stanford University

Mir Z, Bittman S, Townley-Smith L (1987) Voluntary intake and digestibility of complete diets comprised of varying levels of *kochia scoparia* alfalfa hay and barley. Can J Anim Sci 67:1206

Momeni A (2010) Geographical distribution of soil salinity of Iran. Iranian J Soil Sc 24:203–215

Nabati J, Kafi M, Nezami M, Rezvani Moghadam P, Masoumi A, Zare Mehrjardi M (2015) The effect of applying different levels of salinity on some little features and quality of forage kochia. Iranian J Field Crops Res 12:613–620

Norman HC, Masters DG, Barrett-Lennard EG (2013) Halophytes as forages in saline landscapes: interactions between plant genotype and environment change their feeding value to ruminants. Environ Exp Bot 92:96–109

Nowak V, Du J, Charrondière UR (2015) Assessment of the nutritional composition of quinoa (*Chenopodium quinoa* Willd.). Food Chem 193:47–54

Nsimba RY, Kikuzaki H, Konishi Y (2008) Antioxidant activity of various extracts and fractions of *Chenopodium quinoa* and Amaranthus spp. seeds. Food Chem 106:760–766

O'leary JW, Glenn E, Watson M (1985) Agricultural production of halophytes irrigated with seawater. In: *Biosalinity in action: Bioproduction with saline water*. Springer, Dordrecht

Panta S, Flowers T, Lane P, Doyle R, Haros G, Shabala S (2014) Halophyte agriculture: success stories. Environ Exp Bot 107:71–83

Razzaghi F, Ahmadi SH, Adolf VI, Jensen CR, Jacobsen SE, Andersen MN (2011a) Water relations and transpiration of quinoa (*Chenopodium quinoa* Willd.) under salinity and soil drying. J Agron Crop Sci 197:348–360

Razzaghi F, Ahmadi SH, Jensen CR, Jacobsen S-E, Andersen MN (2011b) The salt tolerance of quinoa measured under field conditions. International Congress on Irrigation and Drainage, Teheran, Iran

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 Intl 19:179–189

Sabori S, Nezami M, Banayan Aval M (2011) The estimated minimum optimum and maximum temperature of seed germination Kochia (*Kochia scoparia* L. Schard) using the five-parameter beta. Ageoecolog J 3:191–197

Salehi M (2017a) Determination of best sowing date of quinoa in Yazd province. National Salinity Research Center, Final Report

Salehi M (2017b) Phenologic and morphologic study of different species of Salicornia in Yazd provinces. National Salinity Research center, Final Report

Salehi M (2017c) Selection of the best genotype of quinoa with saline water. National Salinity Research Center, Final Report

Salehi M, Kafi M (2011) Initial irrigation time with saline water on the salt tolerance and ion content of *Kochia scoparia* (L. Schrad) at seedling stages. Spanish J Agric Res 9:650–653

Salehi M, Kafi M, Kiani AR (2010a) Salt stress and deficit irrigation effects on Kochia (*Kochia scoparia* L. Schard) production in summer cropping. International conference on Management of Salt-Affected Soils and Water for Sustainable Agriculture. Paper#005:1-7 Sultan Qaboos University

Salehi M, Sadeghipour HR, Gruber MY, Kiani AR, Kafi M (2010b) Should Kochia be considered seriously as a biofuel feedstock? 10th Agricultural Biotechnology International Conference-Canada

Salehi M, Kafi M, Sadeghipour HR (2011) Using of saline irrigation water on biomass production and ions accumulation in kochia (*Kochia scoparia*). Environ Stress Agronomy 4:65–75

Salehi M, Kafi M, Kiani A (2012a) Salinity and water effects on growth, seed production and oil content of *Kochia scoparia*. J Agron 11:1–8

Salehi M, Kafi M, Kiani AR (2012b) Water-salinity production function of Kochia in the north of Golestan. J Water Soil 25:1395–1403

Salehi M, Kafi M, Kiani AR (2013) Crop coefficient, water productivity, yield response factor of spring Kochia under irrigation regimes and salinity. Iran Water Res J 12:89–97

Salehi M, Soltani V, Banakar MH (2015) Selection of the best clones of *Panicum antidotale* under saline condition. National Salinity Research Center

Salehi M, Soltani V, Dehghany F (2016a) Potential of quinoa production in central plateau of Iran. Regional conference of marginal area of Iran central desert Qom-Iram

Salehi M, Soltani V, Jacobsen SE (2016b) Effect of sowing date on phenological stage and seed yield of quinoa irrigated with saline water. In: Quinoa for future food and nutrition security in marginal environments. ICBA, Dubai

Salehi M, Dehghany F, Ebrahimi NG (2017a) Successful story of Salicornia seed production with saline water. Water Sustain Dev 4:37–41

Salehi M, Dehghany F, Soltani V (2017b) Effect of salinity and seed priming on quinoa emergence. Environ Stress Crop Sci 381:381

Shahbaz M, Iqbal M, Ashraf M (2011) Response of differently adapted populations of blue panic grass (*Panicum antidotale* Retz.) to water deficit conditions. J Appl Bot Food Qual 84:134–141

Shahid M, Jaradat AA, Rao NK (2013) Use of marginal water for Salicornia bigelovii Torr. Planting in the United Arab Emirates. In: Developments in soil salinity assessment and reclamation. Springer, Dordrecht

Short DC, Colmer TD (1999) Salt tolerance in the halophyte *Halosarcia pergranulata* subsp. pergranulata. Ann Bot 83:207–213

Steppuhn H, Wall K (1993) *Kochia scoparia* emergence from saline soil under various water regimes. J Range Manag 46:533–538

Steppuhn H, van Genuchten MT, Grieve CM (2005) Root-zone salinity. II. Indices for tolerance in agricultural crops. Crop Sci 45:221–232

Tavakoli H, Filehkesh I, Kashki V, Bashtini J (2008) Potential of using saline soils and waters for forage production in dry region. In: Kafi M, Khan MA (eds) Crop and forage production using saline waters. Springer, India

Ungar IA (1982) Germination ecology of halophytes. In: Contributions to the ecology of halophytes. Springer, Dordrecht

Ventura Y, Wuddineh WA, Shpigel M, Samocha TM, Klim BC, Cohen S, Shemer Z, Santos R, Sagi M (2011) Effects of day length on flowering and yield production of Salicornia and Sarcocornia species. Sci Hortic 130:510–516

Xianzhao L, Chunzhi W, Qing S (2013) Screening for salt tolerance in eight halophyte species from Yellow River Delta at the two initial growth stages. ISRN Agronomy 2013:1

Yazar A, Incekaya Ç, Sezen SM, Jacobsen S-E (2015) Saline water irrigation of quinoa (*Chenopodium quinoa*) under Mediterranean conditions. Crop Pasture Sci 66:993

Yensen NP (2008) Halophyte uses for the twenty-first century. In: Ecophysiology of high salinity tolerant plants. Springer, Dordrecht

Zevallos V, Herencia L, Ciclitira P (2015) Quinoa, coeliac disease and gluten-free diet. In: Bazile D, Bertero H, Nieto C (eds) State of the art report on quinoa around the world in 2013. FAO, Rome

Chapter 4
Amending Soil Health to Improve Productivity of Alternate Crops in Marginal Sandy Soils of the UAE

Shagufta Gill, Abdullah Alshankiti, Shabbir A. Shahid, and Juan Pablo Rodriguez

Abstract Sandy soils are considered marginal, owing to their low soil fertility, due to their low soil organic carbon and clay contents. The marginality is particularly pronounced when sandy soils exist in hot and arid environments, such as in the UAE and other GCC countries. Three field trials were undertaken in three agricultural seasons, i.e., 2014, 2015, and 2016, on sandy soils, employing various combinations of organic and inorganic soil amendments. The procedures used for the recycling green and date palm residues to compost and biochar, as well as their beneficial uses, are presented and discussed. The addition of organic amendments increased plant growth, height, fresh biomass, and grain yield in quinoa, cowpea, and lablab-bean. The combined use of compost and biofertilizer has a significant impact when compared to biofertilizer application alone. The use of Sharjah-compost can be a viable option and environment friendly method to improve soil health. The use of organic amendments significantly affected organic carbon build up and increased plant growth parameters, which indicate its positive impact on sandy soils.

Keywords Biochar · Bontera™ · Sharjah-compost · Soil organic carbon · Quinoa · Cowpea · Lablab-bean

4.1 Introduction

4.1.1 Marginal Environment

Marginal land with low-quality soil has a little agricultural value with low food production capacities unless efforts to ameliorate land quality are implemented

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(Kirkpatrick 1983; Shahid and Alshankiti 2013). Adequate land and soil can enhance crop productivity; where too poor for crop production, the land can be used for grazing. Marginal lands are areas with minimal precipitation, extreme temperatures, low soil fertility, experience erosion, and shallow lands (depth <50 cm) are salt-affected, have marshy terrain, or present other challenges to agricultural productivity. Marginal lands exist worldwide, according to climatic conditions and geographical occurrence (Anderson 2012).

In the Gulf Cooperation Council (GCC) countries, reduced arable land, water scarcity, and harsh climatic conditions restrict agriculture development. Thus, the agriculture sector is a marginal contributor to their national gross domestic products (GDP), and the population engaged in agriculture varies across different countries. The Economist Intelligence Unit forecasted that GCC countries will increase spending on food imports from US$ 42.6 billion in 2017 to US$ 53.1 billion by 2020 (EIU 2010). The World Integrated Trade Solution (2014) showed that the UAE alone imported food worth US$ 8.10 billion in 2014 alone. Their reliance on food imports is further complicated by the fact that the price of a major source of GCC incomes, oil, has reduced significantly in recent years. There is a great need to improve local agriculture production, both to reduce the dependency on food from other countries and the financial burden of imports.

4.1.2 Emphasis in Improving Soil Quality with Organic Amendments

Sandy soils have low agriculture productivity; improving crop productivity in these lands is essential to increasing food production for growing populations. Experiences in the UAE (Shahid et al. 2013) revealed that sandy soils are plagued with very low water and nutrient holding capacities, which lead to frequent irrigation, high leaching, nutrient losses, and groundwater pollution. Furthermore, hot temperatures combined with scarce rainfall regionally necessitate innovative ways to conserve water, improve soil properties, and prevent nutrient loss. One of the ways to improve agricultural output is to focus on soil health.

In this chapter, the authors have focused on the sandy soils present in the UAE to improve their health, thereby leading to increased crop productivity using amendments. In sandy desert soils, some of the key priorities in agricultural lands are to restore degraded soil nutrient pools, improve the on-farm recycling of nutrients, and increase the nutrient use efficiency. Therefore, any technology that enhances water and nutrient use efficiency, as well as increases crop production, should be considered a research priority for irrigated agriculture in marginal environments with water and arable land scarcities. Integrated Soil Fertility Management (ISFM), which combines the use of organic and inorganic soil additions to improve soil productivity, can significantly increase crop yield, rebuild depleted soils, and protect the natural resources (Evans 2009).

At present, the use of biochar and organic amendments to improve soil health and intensify agriculture in marginal desert environments is gaining prominence (Gill et al. 2016). Thus, it is imperative to improve properties of sandy soils in terms of biological activity, as well as their retention of moisture and nutrients. This will help improve water use efficiency and prevent groundwater pollution caused by leaching of nutrients, such as nitrates. Such an improvement is only possible when the sandy soils are amended with inorganic and/or organic (such as compost, biochar) materials to improve soil health for plant growth. Recycling green waste from urban landscapes and agricultural farms compost, as well as woody (high lignin) material to biochar, is gaining traction internationally. These materials are being reused as green waste to improve soil quality, thus avoiding landfills and protecting the environment. The use of these materials also enhances soil carbon (C) sequestration, which leads to increased crop productivity and, hence, reduces the gap between food/feed import and national production, which saves financial resources.

4.1.2.1 What Is Biochar?

Biochar (BC) is a charcoal produced when biomass undergoes the process of pyrolysis, i.e., when biomass is heated in an oxygen-poor environment to avoid combustion (Lehmann and Joseph 2009). Biochar is a heterogeneous mixture with physicochemical properties and its agronomic, environmental advantages can improve water retention in weak structured soils (Lian and Xing 2017). Its addition to soils increases their carbon sequestration and improves their soil fertility by enhancing nutrients retention (Bruun et al. 2011; Zhang et al. 2013; Zhai et al. 2014).

4.1.2.2 Why Biochar Production in the UAE?

The utilization of biochar on sandy soils in the UAE is intended to improve their soil properties and crop production. Over 40 million date palm trees are grown in the UAE; more than three-quarters of them in the Emirate of Abu Dhabi. Each tree approximately generates 15 kg of waste biomass per year, totalling approximately 600 million kg annually. Unmanaged green waste from date palms can end up in landfills, thereby leading not only to wastage of precious biomass but also increasing the burden of waste on the environment. Handling this significant quantity of green waste in a sustainable way must be considered. Using date palm biomass for the generation of biochar for use as a soil conditioner may be one of the possibilities for an environment-friendly option for handling the waste. Scientists at the International Center for Biosaline Agriculture (ICBA) have taken the initiative and established a pilot scale biochar production facility at experimental station (Fig. 4.1).

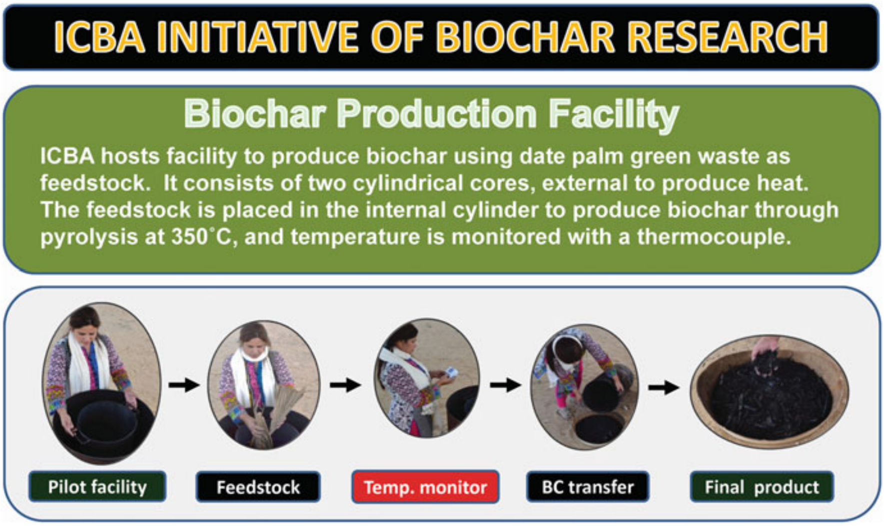

Fig. 4.1 ICBA initiative of low-cost biochar production

4.1.2.3 Benefits of Biochar Uses

The use of biochar in agricultural fields improves soils, through the enhancement of physical (soil structure, bulk density, moisture retention), chemical (cation-exchange capacity), nutritional (nutrient use efficiency), and microbial (improved growth of soil microbes is essential for nutrient absorption, particularly mycorrhizal fungi) properties, leading to increased crop production and environmental protection. The use of locally produced biochar reduces dependency on imported soil conditioners, saving financial resources, which ultimately leads to increase crop productivity and reducing gaps between food/feed import and local production.

4.1.2.4 Biochar Effects on Soil Properties

Biochar improves crop production through a direct modification of soil properties; its addition modifies the nutrient and physical characteristics of the soil, through the provision chemically active surfaces. BC use benefits to root growth in plants, as well as nutrient and water retention.

4.1.2.5 Pilot Scale Low-Cost Production of Compost from Green Waste Material

Compost is often the most economical source of organic matter. The manipulation factors for composting are done mainly to enhance the microbial activity. Microbial inoculants increase the process of composting and the nutrient content of the finished product, which further enhances the crop yields.

Heretofore, there are increased concerns about the excessive use of chemical fertilizers, atmospheric pollution, soil health, and biodiversity. There is much global interest in organic recycling practices. Composting is an attractive proposition for converting on-farm green waste to beneficial end product-compost. The objective of low-cost compost production at ICBA (Fig. 4.2) is to develop techniques that enable the smallholder farmers to recycle on-farm green waste to beneficial compost and use it to improve farm soil quality, thereby increasing agricultural production. In the low-cost compost production methods deployed, feedstocks derived from plants clippings (grass, shrubs, ground cover, and trees) were piled, and moisture was maintained at 40–50%. Manual turning of the material was completed on alternate

Fig. 4.2 Low-cost compost production technologies at ICBA

days. After the second week, the material was inoculated with a cluster of microbes (fungi, *Actinomycetes*, mycorrhiza, *Trichoderma*, and bacteria) to enhance the composting process. Due to this process, the matured compost was ready to use after 8–10 weeks instead of routine composting times of 20–24 weeks.

The compost quality depends on the source and quality of the feedstock used. Various studies have quantified the beneficial uses of compost on agriculture, crops, and environment (Rodd et al. 2002; Rahman et al. 2006). Pérez Piqueres et al. (2006) found that the impact of compost on soil characteristics is dependent on both the properties of the compost and the soil it is added to. Furthermore, in addition to the proven benefits composts have on the physical structures of soils (Postma et al. 2003), composts also can provide biological control of many disease pathogens through microbial actions, particularly soilborne pathogens.

The soil organic matter (SOM) is critical for plant growth, as it provides microorganisms their main source of energy and plants a major nutrient supply. Microbes such as bacteria, fungi, and other microfauna representatives are responsible for energy and nutrient cycling and regulation of SOM transformations (Zech et al. 1997). The major effect of SOM in mineral soils is its contribution of 20–80% of the cation-exchange capacity (CEC). The SOM influences soil physical properties by promoting aggregation. And, for critical nutrients like N, P, and K, compost promotes their slow release and ensures their long-term storage (Sullivan et al. 2002). However, the addition of compost is not considered the sole source of nutrients, and, hence, it is integrated with chemical and biofertilizers to offset the nutrient requirements of crops.

4.1.3 Alternative Potential Crops for Marginal Desert Lands

Amaranthaceae family species include wild, cultivated, leafy, and grain crop species that are suitable to arid geographical regions. Crops like quinoa (*Chenopodium quinoa*), amaranth (*Amaranthus caudatus*), and cañahua (*Ch. pallidicaule*) grow in sandy soils with low fertility and can thrive even with low levels of fertilizers use. Moreover, these crops can withstand harsh environments where low temperatures, high stress, and low precipitations occur (Choukr-Allah et al. 2016; Bhargava and Srivastava 2017; Rodriguez et al. 2020b). These crop plants provide nutritive gluten-free grains and biomass with high protein content, which in their fresh and dry state are used as food and fodder. In 2016 Peru, Bolivia, and Ecuador were the main producer and supplier of organic quinoa to the world. In 2016, 101 countries in the world introduced and adapted quinoa (Alandia et al. 2016). Organic arable crops including quinoa and amaranth are grown in significant portions of farmland in Bolivia (87,000 ha) and Peru (6000 ha, mainly quinoa). The Andean grain occupies nearly 95,000 ha of land in those two countries alone, which represents more than 70% of quinoa cultivated in the region (Willer and Lernoud 2017).

In the UAE, there has been an increase in the number of farmers specialized in crop production under desert conditions (Willer and Lernoud 2017). Most of the soils in the UAE are sandy with low fertility and are fed by saline groundwater. Choukr-Allah et al. (2016) and Rao and Shahid (2012) have highlighted five quinoa cultivars that performed well in four locations in the UAE. Yet, agronomic management is needed to improve the plant establishment and seed yield per plant. Appropriate soil enhancements are needed for sustainable quinoa production and other alternative crops.

Compost helps soil structural development to increase moisture and nutrient retention in soils; however, planting nitrogen-fixer plants like legumes can further enhance these effects. Legumes include important grain, pasture, and agroforestry species, and they are well adapted to growth in sandy soils. The potential for leguminous crops as food source and for fertility replenishment is well established, as it has been tested successfully in sub-Saharan Africa, though the rate of their adoption is slow and thus fails to contribute significantly to rural livelihood improvements (Mpepereki et al. 2000; Giller 2001; Mekuria and Waddington 2002). Cowpea and lablab-bean grow in clay and fertile to poor sandy soils. However, on well-drained soils, i.e., sandy loam at pH of 6–7, they can reach their highest seed yields (Prota 2006).

Cowpea or black-eyed peas (*Vigna unguiculata* (L.) Walp) is a crop adapted and grown in tropical regions, specifically in African countries. Nevertheless, the introduction and adaptation of cowpea to UAE through ICBA research showed great promise for it to serve as a cover crop that facilitate fertility restoration and can be utilized for biomass and seed production (Rao and Dakheel 2015; Rao and Shahid 2011). Cowpea seed yield under sandy soil conditions reached up to 3.09 t ha^{-1} (Rao et al. 2009). Similar response was observed in lablab-bean (*Lablab purpureus* (L.) Sweet), an African orphan crop production under conditions of the UAE. Besides, the wild relatives of lablab-bean in Saudi Arabia and Yemen reported by Rao (2013) stressed its potential for arid agriculture as native species to this arid geographic region. Thus, the combined use of organic amendments and planting of regionally suitable leguminous crops may contribute to the improvement of soils and food production in the UAE.

4.1.4 Performance of Alternative Crops Under Marginal Conditions: Case Study UAE

Since 2007, the Dubai-based ICBA partnered with the Ministry of Climate Change and Environment (MOCCAE) of the UAE, the Abu Dhabi Farmers Service Center (ADFSC), as well as its Peruvian partners the Instituto Nacional de Investigacion Agraria (INIA) and the Universidad Nacional Agraria La Molina, (UNALM) to evaluate several quinoa cultivars for marginal conditions (Choukr-Allah et al. 2016; Rao and Dakheel 2015). ICBA started with the screening 121 quinoa germplasm accessions provided by the United States Department of Agriculture (USDA) in 2006 in Dubai, UAE. The output of this screening provided 20 promising quinoa accessions. Later, in two agricultural seasons, 2007/2008 and 2008/2009, five prominent quinoa cultivars were selected within the 20 quinoa cultivars with high seed yield and biomass for arid and desert regions of UAE localities (Rao and Shahid 2012; Choukr-Allah et al. 2016).

In the UAE, ICBA has also introduced and investigated the suitability of cowpea and lablab-bean for arid conditions and low fertility soils. Rao and Shahid (2011) conducted investigations to study alternative crops, like cowpea, which have low water requirements. A total of 23 accessions of cowpea were screened in summer 2009 (120 days) in Dubai. Dry matter yields of the accessions averaged of 18.1 t ha^{-1}, and the accession TVu 9480 had the highest yield (24 t ha^{-1}). Seed yield of cowpea accessions ranged from 1.1 t ha^{-1} (acc. TVu 9604) to 4.9 t ha^{-1} (acc. TVu 9510). In relation to lablab-bean, Sharma et al. (2013) has characterized salt-tolerant rhizobia native in three accessions of lablab-bean. This finding indicates that this crop not only provides seed yield but can also be used as forage for livestock feeding, making its adaptation to saline and sandy soils conditions highly advantageous.

This chapter outlines results of two studies using three alternative crops for sustainable production of biomass and seeds using organic amendments that improved sandy soil fertility. The aims of the studies were to further understand the impacts of (1) biochar and chemical fertilizers on quinoa and cowpea production, (2) composts and biofertilizer on the yield of lablab-bean and cowpea, and (3) soil improvement, particularly in organic carbon buildup.

4.2 Materials and Methods

4.2.1 Plant Material

The first experiment utilized seeds of quinoa cultivar ICBA-Q5 and cowpea (ILRI 12713) from the experimental station of ICBA. Meanwhile, the second experiment used seeds of cowpea cultivar (ILRI 12713) and lablab-bean (PI 183451).

4.2.2 Experiment I

4.2.2.1 Use of Biochar and Chemical Fertilizers on Quinoa and Cowpea Production

The experiment was conducted on sandy soils representative of the types that dominate in the UAE and GCC countries (Shahid et al. 2013). The experimental site consisted of nine plots (3 m × 3 m) of 9 m^2 area. Triplicate plots received the following treatments: (1) control + NPK; (2) biochar, 20 t ha^{-1} + NPK (standard); and (3) biochar, 30 t ha^{-1} + NPK (standard). Plots were arranged in a completely randomized design (CRD). Biochar was incorporated into the top 15 cm of the soil and thoroughly mixed. For irrigation, a drip system was used. Evapotranspiration (ET) was determined by an automatic meteorological station and was used to calculate the crop water requirements. Seedlings of quinoa and cowpea were first planted in jiffy pots and were later transplanted along dripper lines in the experimental field plots after the development of eight real leaves. Dripper lines had a 0.5 m spacing, and the distance between plants was 0.25 m.

4.2.3 Characteristics of ICBA Soil

The ICBA experimental station in Dubai possesses sandy, nonsaline ($EC_e < 2$ dS m^{-1}) and moderately alkaline soils (Table 4.1). The pH is slightly higher than the optimum range (6.7–7.3), at which most of the nutrients are available to plants. Soil texture at the first horizon is comprised of fine sands. The soil is strongly calcareous with high buffering capacity. The nutrients (NPK) are lower in fertility status. Field capacity in sandy soils denotes lower water holding capacity and high drainage capacity, which need careful management to improve water and nutrient use efficiencies.

4.2.3.1 Irrigation and Irrigation System: Cowpea and Quinoa Crops

Saline water (5.10 dS m^{-1}) with a sodium adsorption ratio (SAR) of 12.21 $(mmoles/l)^{0.5}$ was used to offset the water requirement of the cowpea and quinoa crops in 2016–2017 (Table 4.2). A drip irrigation system was used with an emitter spacing of 50 cm. The plots were irrigated twice daily, for 5 min in the morning and evening. Emitter flow rates were adjusted at 4 L per hour.

Table 4.1 Soil characteristics at the beginning of the experiment

Soil characteristics	Exp. 1	Exp. 2
Electrical conductivity of soil saturation extract (EC_e: dS m^{-1})	1.65	1.64
pH of saturated soil paste (pH_s)	7.5	7.6
Total N (mg kg^{-1})	27.57	60.71
Total P (mg kg^{-1})	24.95	6.73
Total K (mg kg^{-1})	67.77	78.77
Organic matter content (%)	0.201	0.197
$CaCO_3$ (equivalents) (%)	54	53
Field capacity (%)	6	6

Table 4.2 Analysis of water used in the irrigation

	Exp. 1
Parameters of irrigation water	2016
Electrical conductivity (dS m^{-1})	5.10
pH	7.11
Na^+ (meq L^{-1})	28.1
Ca^{2+} + Mg^{2+} (meq L^{-1})	10.6
K^+	0.79
HCO_3^- (meq L^{-1})	1.2
Cl^- (meq L^{-1})	35.6
Sodium adsorption ratio (SAR: Mmoles/ L)$^{-0.5}$	12.21
Residual sodium carbonates (RSC: Meq L^{-1})	–
Water class (very high salinity and medium sodium)	C4S1

Table 4.3 Characteristics of biochar derived from date palm waste

Features	Biochar
Moisture (%)	6.52
Ash (%)	24.9
pH (1:10 biochar: water suspension)	8.90
EC (dS m^{-1}) (1:10 soil: water extract)	2.5
Cation exchange capacity (c Mol $^{(+)}$ kg^{-1})	16.9
Organic carbon (%)	43.6
Total nitrogen (mg kg^{-1})	7.02
Total phosphorus (mg kg^{-1})	15.79
Total potassium (mg kg^{-1})	7.95

4.2.4 Characteristics of Biochar

The color of biochar produced from date palm is grayish black and comparable (Table 4.3) to that recorded by Al-Wabel et al. (2013). They found that the biochar had high EC, pH, and ash contents at 350–400° C of relative temperature when the biochar was prepared from date palm waste. High temperatures can increase the pH and the loss of functional groups, thus increasing alkalinity. The cation exchange capacity (CEC) is reasonable and demonstrates the potential to increase nutrient and water retention when used in agricultural fields.

4.2.5 Particle Size Distribution Analyses (PSDA) of Biochar Material

The biochar was fractionated by passing from sieves (0.25, 2, and 5 mm) and revealed its distribution in three size fractions: 2–5 mm (73.76%), followed by

0.25–2 mm (18.35%), with the least quantity in >5 mm (7.89%). The fractionate percentages were calculated by mass of the particle groups.

4.2.6 *Experiment II*

This experiment was conducted in two agricultural seasons in sandy soil fields. The first field trial (each plot 9 m^2 under randomized complete block design-RCBD) was carried out in 2014–15 with four treatments: (1) control, (2) ICBA-compost (20 t ha^{-1}), (3) Sharjah-compost (20 t ha^{-1}), and (4) Bontera™ (5 L ha^{-1}). A second experiment was conducted under similar conditions to the first. It was held in 2016 with four treatments as well: (1) control, (2) ICBA-compost (20 t ha^{-1}), (3) Sharjah-compost (20 t ha^{-1}), and (4) ICBA-compost + Bontera™ (5 L ha^{-1}). The ICBA-compost and Sharjah-compost were split applied at the rate of 20 t ha^{-1} a month before and after sowing. The compost was incorporated to upper 15 cm depth. In a separate treatment, Bontera™ was spread to leaf of plants (foliar spraying) in two splits (2.5 L ha^{-1} each split) at the time of sowing and after 1 month. Seedlings of cowpea and lablab-bean were first planted in jiffy pots and were later transplanted besides of dripper lines in the experimental field plots after the development of eight real leaves. Dripper lines were spaced 0.5 m and distance between plants was 0.25 m. Each treatment was applied in four randomly replicate plots. Plant growth variables (height, dry biomass, and grain yield) were measured to find out differences between treatments and crops. After harvesting, the plants were dried, and physical quality seed analysis was carried out at the laboratory.

4.2.6.1 Irrigation and Irrigation System: Lablab-Bean and Cowpea Crops

Fresh water (0.308 dS m^{-1}) was used to offset the water requirement of the leguminous crops in 2014–2015, and then irrigation was switched to saline water (EC = 4.05 dS m^{-1}; SAR 9.10 $(mmoles/L)^{-0.5}$) in 2016 (Table 4.4). Drip irrigation system was used with emitter spacing 50 cm. The plots were irrigated twice daily, 5 min in the morning and 5 min at evening. The emitter flow rate was adjusted at 4 L per hour.

4.2.7 *Characteristics of Utilized Compost*

Table 4.5 shows chemical characteristics of compost prepared at ICBA and Sharjah-compost. The compost is rich in organic matter content and presents very dark brown color (Munsell notation), EC is at low range, and pH is slightly alkaline and NPK

Table 4.4 Features of water used in the irrigation

	Exp. 2	
Water quality features	2014–2015	2016
Electrical conductivity (dS m^{-1})	0.308	4.05
pH	7.56	7.15
Na^+ (meq L^{-1})	1.59	25.10
Ca^{2+} + Mg^{2+} (meq L^{-1})	1.24	15.20
K^+	0.04	–
HCO_3^- (meq L^{-1})	0.10	1.74
Cl^- (meq L^{-1})	0.20	34.50
SO_4^{2-} (meq L^{-1})	2.57	4.06
Sodium adsorption ratio (SAR: Mmoles/L)$^{0.5}$	2.02	9.10
Residual sodium carbonates (RSC: Meq L^{-1})	–	–
Water class	C2S1	C4S1
C2 (medium salinity), S1 (low sodium), C4 (very high salinity)		

Table 4.5 Physical and chemical characteristics of compost

Compost features	ICBA-compost	Sharjah-compost
pH	7.7 (1:10)	6.81 (1:5)
Electrical conductivity (dS m^{-1})	2.25 (1:10)	3.9 (1:5)
Organic matter content (%)	38.15	42.41
Total N (%)	0.67	2.5
Total P (%)	0.27	1.92
Total K (%)	0.75	0.50
Moisture content (%)	8	8–10
Color	Very dark brown	Dark brown
Nature (origin)	Plants clippings	Green waste and sludge

less than 1%; this shows good quality status to some extent, but it cannot completely replace fertilizers.

4.2.7.1 Data Collection

In experiment I, after the harvesting of cowpea in 2016, the quinoa cultivar was planted in the same plots in September 2016 to study the residual effect of biochar, using three treatments with three replicates as mentioned above. Crop growth parameters (fresh biomass, grain yield) were determined to evaluate the response of various treatments. Quinoa plant fresh biomass and seeds were collected manually and their weight for various treatments dried at 60 °C in a stove for 24 h, and data was recorded.

4.3 Results and Discussion

4.3.1 *Experiment I*

4.3.1.1 Quinoa

Applying biochar (30 t ha^{-1}) lead to significant increases in the fresh biomass of quinoa relative to the control treatment with only NPK (Fig. 4.3a). This increase was 54 and 113% with the application of 20 and 30 t ha^{-1} of biochar, respectively. Similarly, seed weight per plant also increased by 116 and 153% with the application of 20 and 30 t ha^{-1} of biochar, respectively (Fig. 4.3b). In contrast control treatment had low fresh biomass and seed yield. Organic fertilization had a significant effect on productivity of quinoa genotype ICBA-Q5 in a native sandy soil. Rodriguez et al. (2020a, b) found that sowing density did not affect harvest index but affected plant biomass in four quinoa genotypes (ICBA-Q3, ICBA-Q5, Amarilla Sacaca, Titicaca) in the three localities (Dubai, Al Dhaid, and Abu Dhabi). We found either significant differences between in fresh biomass of two genotypes (ICBA-Q3 and ICBA-Q5) in Dubai (2016–2017). In UAE, genotypes, rather than environmental characteristics, are the major determinant of harvest index for quinoa crops. Hot temperatures during flowering and seed development can contribute to substantial variation in harvest index. ICBA-Q5 quinoa genotype produced high grain yields (Rodriguez et al. 2020b). During phenological evaluations of ICBA-Q5 in Al Dhaid (another trial on sowing dates not published yet), this genotype had an earlier flowering time than ICBA-Q3.

Biochar used at 20 and 30 t ha^{-1} had a significant effect on biomass and grain yield in sandy soils typical to the local deserts (Dubai, UAE); when combined with a low rate of inorganic fertilizer, they could affect the growth of maize (Alshankiti and Gill 2016) and quinoa, according to the findings of this study. Date palm waste is

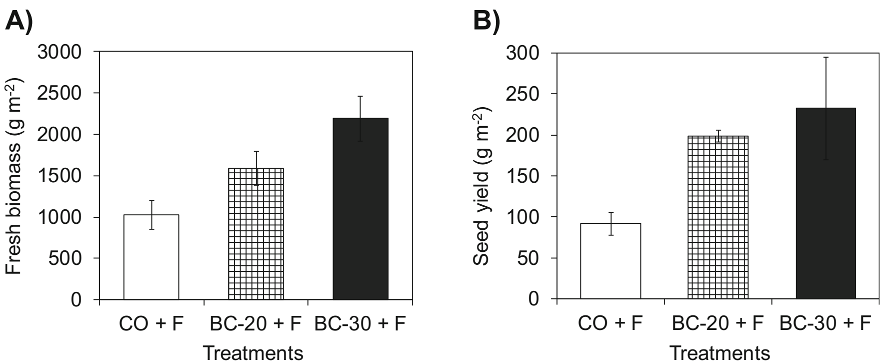

Fig. 4.3 Plant and seed weight of quinoa cultivar ICBA-Q5, (**a**) fresh biomass and (**b**) seed. Average values (means ± S.D.; $n = 16$). Treatments consisted in control (CO) and two levels of biochar at 20 and 30 t ha-1 (BC-20, BC-30) combined with fertilizers (F) of NPK

available in the UAE, and the making of biochar, which is not complicated in its production, is a demonstrated potential source for growing alternative crops (Kwapinski et al. 2010; Usman et al. 2015; Haider 2016). Though irrigation for quinoa was lower (at 2 l h^{-1}), organic matter had a more significant role for quinoa grain and biomass production in soils with a low organic matter content, a finding corroborated by similar findings for fodder crops grown in sandy soils (Alshankiti and Gill 2016).

4.3.1.2 Cowpea

Figure 4.4 shows a significant increase in fresh biomass of cowpea with biochar (30 t ha^{-1}) over the control treatment. Fresh biomass was 16 and 27% with the application of biochar of 20 and 30 t ha^{-1}, respectively. Seed biomass and yield were not determined due to long crop growth cycles.

After a review of 24 studies that examined the addition of biochar to soil, Lehmann and Rondon (2006) found improvements in productivity ranging from 20 to 220% due to the application of 0.4–8 tons carbon ha^{-1} to the soil, whereas Steiner et al. (2007) doubled maize yields by using a combination of NPK fertilizer with charcoal instead of NPK fertilizer by itself. This improvement in crop yields is attributed to several factors including enhanced availability of nutrients (Steiner et al. 2007; Major et al. 2010), reduced leaching of applied nutrients thereby leading to increased fertilizer use efficiency (Chan et al. 2007), as well as reduced percolation of water (Lehmann et al. 2003; Steiner et al. 2008; Major et al. 2010) thus ensuring higher and sustained water availability to the crop.

4.3.1.3 Residual Effect of Biochar Application on Soil Properties After Cowpea Harvesting

Numerous studies have quantified the effects that biochar has on the physicochemical properties of soil. It can assist with the maintenance of SOM levels, increase the

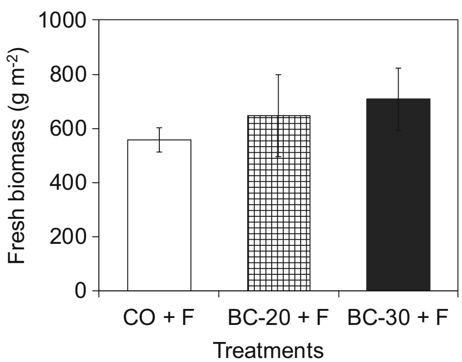

Fig. 4.4 Fresh biomass of cowpea cultivar. Average values (means ± S.D.; $n = 16$). Treatments consisted in control (CO) and two levels of biochar at 20 and 30 t ha-1 (BC-20, BC-30) combined with fertilizers (F) of NPK

efficiency of fertilizer use, and increase overall crop production; it can have long-term positive impacts in subtropical and tropical regions (Chan et al. 2007, 2008; Deenik et al. 2011; Van Zwieten et al. 2010).

Table 4.6 shows the results of soil analysis before and after harvesting the cowpea. Biochar application influenced the increase in soil salinity (ECe) after the harvesting of cowpea (EC = 10 dS m^{-1}). In sandy soil and under conditions of the UAE, biochar from date palm waste and high temperature may had influenced the increase in soil salinity. In contrast, biochar from pecan shells, pecan prunings, and yard wastes can derive a low salinity in the soil (1.28, 2.00, and 1.25 dS m^{-1}) (Zhang et al. 2016). The soil pH remains unchanged besides slight differences. Parameters such as N, P, K, SOM, and CEC has also increased over time; however, the increase was due to increasing rate of biochar. With the application of 20 and 30 t ha^{-1} biochar in the quinoa crop, SOM increase was 188 and 211%, respectively, over control treatment; CEC increased to 34 and 49%, respectively (Table 4.7). After the employment of crop rotation with cowpea-black-eyed-peas crop and due to the biochar amendment (20 and 30 t ha^{-1}) application, electrical conductivity in the soil increased significantly in the plot. Soil pH remained unchanged. The SOM increased by 271–295%, and the cation exchange capacity of soil also increased by 36–52%, with higher increases found in plots with higher rates of addition. Likewise, there was a substantial increase in N, P, and K content of the soil. Several reports have also found changes in physicochemical characteristics of soil that ultimately translate into high soil quality (Carter et al. 2013). Ouyang et al. (2013) and Usman et al. (2015) and Haider (2016) reported significant effect of biochar on aggregate formation and hydraulic properties and soil water holding capacity by 30%. Improved aggregate formation will be of immense significance for sandy soils that lack structure.

After the harvest of cowpea, it was observed that soil salinity increased by between 10.75 and 12.29 dS m^{-1}, therefore, the reclamation irrigation was accomplished using fresh water to reduce residual soil salinity to about 4.5 dS m^{-1}. At this stage, quinoa was planted to assure good germination, emergence, and plant growth.

4.3.2 Experiment II

The results of the 3-year experiments with the two leguminous crops revealed that SOM content increased significantly (Tables 4.6 and 4.7). The combined application of compost (organic fertilizer), Bontera™, Sharjah-compost, and ICBA-compost has increased biomass, grain yield, plant height, and soil organic carbon. Compost is particularly helpful in building up the organic matter due to stabilized carbon and less susceptibility to further decomposition.

Table 4.6 Characteristics of soil with cowpea crop before and after BC application in 2014–2015

	ECe (dS m^{-1})		pH		N (mg kg^{-1})		P (mg kg^{-1})		K (mg kg^{-1})		SOM (g kg^{-1})		CEC (cm kg^{-1})	
Tr.	Bef	Aft	Bef	Aft	Bef	Aft	Bef	Aft	Bef	Aft	Bef	Aft	Bef	Aft
T1	1.65	10.75	7.51	7.50	27.57	129.07	24.95	25.97	67.77	82.68	2.0	2.6	3.25	3.34
T2	1.57	11.81	7.45	7.50	26.67	167.58	24.76	35.39	68.50	127.64	1.9	7.5	3.20	4.48
T3	1.62	12.29	7.50	7.49	27.56	169.11	23.65	54.37	69.10	139.41	1.9	8.1	3.31	4.98

Before (bef), after (aft), and (Tr.) treatments that consisted in T1 (control and fertilizers: CO + F), T2 (biochar at 20 ha^{-1} A and fertilizers: BC-20 + F), T3 (biochar at 30 ha^{-1} A and fertilizers: BC-30 + F). The fertilizers (F) consisted in NPK

Table 4.7 Features of soil with quinoa cv. ICBA-Q5 before and after BC application in 2016

	ECe (dS m^{-1})		pH		N (mg kg^{-1})		P (mg kg^{-1})		K (mg kg^{-1})		SOM (g kg^{-1})		CEC (cm kg^{-1})	
Tr.	Bef	Aft	Bef	Aft	Bef	Aft	Bef	Aft	Bef	Aft	Bef	Aft	Bef	Aft
T1	4.56	4.25	7.20	7.31	120.57	231.8	24.95	34.90	69.03	80.55	1.9	2.1	3.25	3.30
T2	4.34	4.52	7.25	7.20	131.56	256.5	25.87	39.04	70.12	120.57	2.1	7.8	3.20	4.51
T3	4.40	4.34	7.34	7.68	140.67	254.2	26.17	44.87	71.17	137.90	2.2	8.3	3.25	5.01

Before (bef), after (aft) the stablished crop, and (Tr.) treatments that consisted in T1 (control and fertilizers: CO + F), T2 (biochar at 20 ha^{-1} A and fertilizers: BC-20 + F), T3 (biochar at 30 ha^{-1} A and fertilizers: BC-30 + F). The fertilizers (F) consisted in NPK

4.3.3 Plant Height

4.3.3.1 Lablab-Bean

Figure 4.5 shows that the plant height (or vigor) of the lablab-bean improved significantly over the 3 years of trials in soil amended with ICBA-compost and Sharjah-compost. Plant height improved 38%, from 89 cm in 2014 to 144 cm, in 2016 in soil amended with ICBA-compost; respective values for Sharjah-compost were 97–152 cm, amounting to a 36% improvement. Small improvements in unamended soils were also observed. However, soils receiving Bontera™ and compost had around 30% better plant vigor, i.e., from 88 cm in 2014 to 127 cm in 2016. Plant height was almost unchanged in control soil showing values of 73, 74, and 77 in years 2014, 2015, and 2016, respectively.

Foliar spraying of Bontera™ (BT) led to substantial increases in plant height in both years of application, i.e., 2015 and 2016 (Fig. 4.7). The impact was more pronounced in the control and BT treated soils, i.e., under relatively poorer soil conditions; the control showed the most impact of foliar application of Bontera™. On average, of the four soil treatments including the control, the impact of foliar spray was less in 2016 compared to 2015. Lablab-bean performed better with foliar application of Bontera™ when compared to cowpea. The average significant impact for the 2 years was 23% for Lablab-bean, significantly higher than the 9% for cowpea over the 2 cropping years.

4.3.3.2 Cowpea

Overall increase of plant height from all treatments was observed to be 27% over the control. Application of Sharjah-compost performed better (increase of 29% non-spray; 37% with spray) and minimum increase being (10% non-spray, 14% with spray) with Bontera™ as compared to treatment control (not biofertilizer or not Bontera™) in cowpea. Bhargava et al. (2007), and Schlick and Bubenheim (1996) have reported increase of plant height varying from 52 to over 160 cm due to varietal differences and the specific cultural and agronomic practices adopted. It is worth

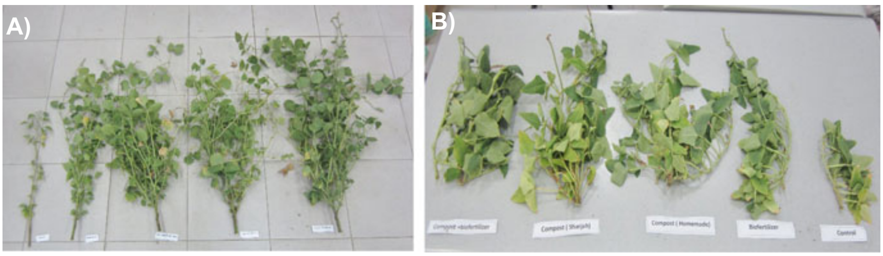

Fig. 4.5 Comparative presentation of plants height of (a) lablab-bean and (b) cowpea (right to left—control, Bontera™, ICBA-compost, Sharjah-compost, ICBA-compost + Bontera™)

mentioning that the sole application of biofertilizer in soil did not substantially impact the plant heights (e.g., 61 and 66 cm in 2014 and 2015). However, when Bontera™ was applied in combination with ICBA-compost, the plant height was 72 cm in 2016 (Fig. 4.6). Plant height is considered an important yield component (Rehman et al. 2010). Foliar feeding or spraying in the leaves had significant effect on plant height. An increase of 20 and 34% was observed in the years 2015 and 2016. Laird et al. (2001) and Nyamangara et al. (2003) have also reported improvements of agricultural soils when they are amended with compost and other organic materials. The amendments improved the physical, chemical, and biological properties and water saving capacity of the soil, which enhances the long-term sustainability of agriculture.

The trend of relative increases of plant heights under treatments ranges in the order of Sharjah-compost > ICBA-compost > Bontera™ > control. In a paper by Rehman et al. (2010), they asserted that plant height is a more important yield component than plant canopy, as when plant height is higher, there will be more photosynthetic activity, resulting in an improved grain yield. These studies demonstrated the effectiveness of organic fertilizers (fertilizers derived from animal matter, animal manure, human excreta, and vegetable matter, like compost and crop residues) as well as biofertilizers (solid and liquid substances containing living microorganisms) to improve plant growth. The organic and biofertilizers performed better compared to recommended inorganic fertilizers. During 3-year field trials, their research confirmed that different organic amendments and their application methods can significantly promote plant growth and improve crop yield and soil organic matter.

4.3.4 Fresh Biomass

Fresh biomass of leguminous crops under different treatments over the 3-year period has shown significant differences. The average fresh biomass of lablab-bean and cowpea crops is presented.

4.3.4.1 Lablab-Bean

Fresh biomass yield of lablab-bean increased over 3 cropping years irrespective of the soil treatment. Higher fresh biomass was produced in soil amended with Sharjah-compost followed by ICBA-compost, both were higher than in the control (Fig. 4.7). Foliar spray with Bontera™ also led to significant increase in biomass compared to the control (no Bontera™ application) in 2014 and 2015 and in 2016 following compost addition. The average impact was 3% and 6% for different soil treatments (including control) in the years 2015 and 2016, respectively. Similar impacts on biomass were identified for cowpea in 2015 and 2016 (i.e., 8.9%). Singh et al. (2001) have reported application of organic fertilizer and biofertilizers (Bontera™)

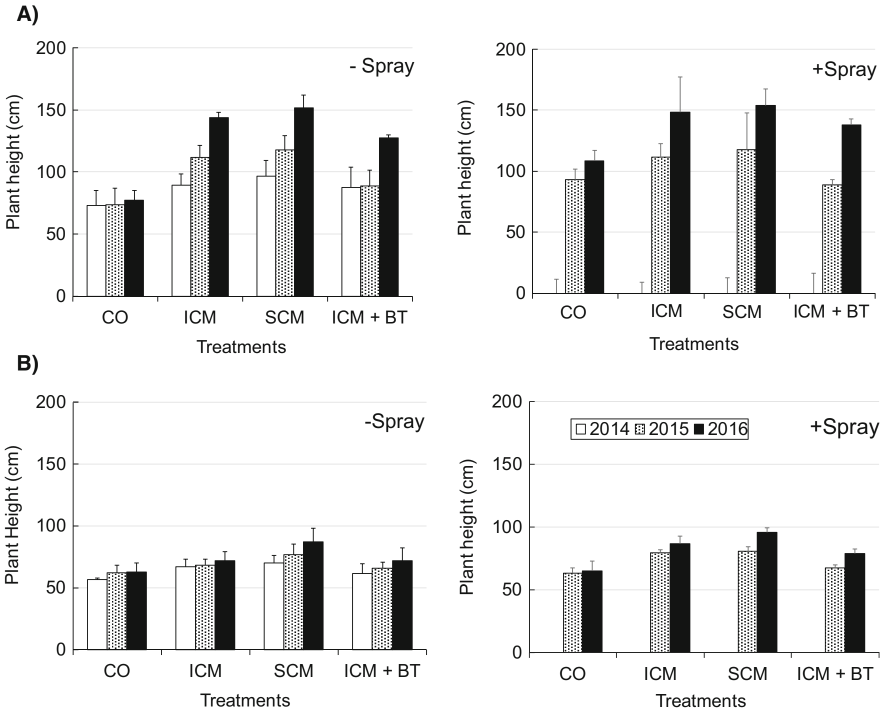

Fig. 4.6 Plant height of (**a**) lablab-bean and (**b**) cowpea without (−spray) and with (+ spray) application of Bontera™ combined in treatments: CO, control; ICM, ICBA-compost; SCM, Sharjah-compost; and BT, Bontera™

promoted plant growth, yield, and quality of rice biomass. They attributed the improvements to the increased rate of nutrient mobilization by microorganisms and the subsequent release of these nutrients during the mineralization process (Sakala et al. 2000). It is believed that many treatments have the potential to improve soil quality through transport of water-soluble nutrients to the roots across the surface resulting in better plant growth (Benbi and Richter 2003), and the use of compost had effect on plant growth, biomass, and seed yield.

4.3.4.2 Cowpea

Organic matter additions improve soil health and results in higher biomass production compared to low fertile sandy soils. Ouédraogo et al. (2001) and Bonanomi et al. (2014) recommend the use of compost for conventional and biological agriculture systems to improve soil fertility and crop yield. Figure 4.7 depicts the effect of organic amendments on the fresh biomass of cowpea. The amount of fresh biomass ranged from 0.07 (control) to 0.29 kg m^{-2} for Sharjah-compost treatment in the trial with non-spray. In the case of biofertilizer application as a spray, the range of fresh

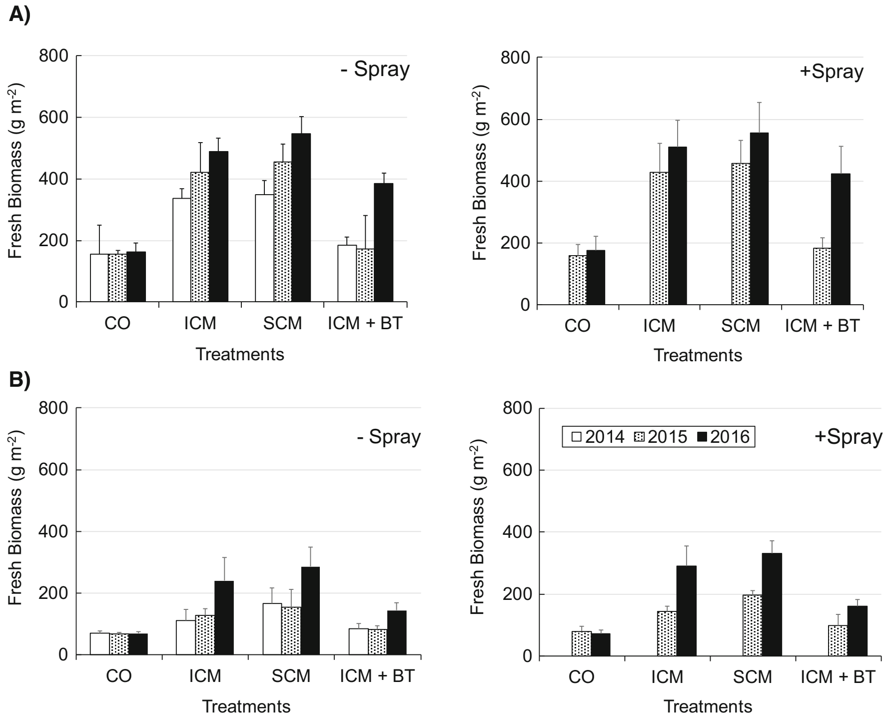

Fig. 4.7 Fresh biomass yield of (**a**) lablab-bean and (**b**) cowpea without (−spray) and with (+ spray) application of Bontera™ combined in treatments: CO, control; ICM, ICBA-compost; SCM, Sharjah-compost; and BT, Bontera™

biomass was 0.07 (control) to 0.33 kg m^{-2} with Sharjah-compost. In contrast, there was a wide variation of fresh biomass amounts within the different treatments, which is shown in Fig. 4.7.

Rice straw compost, when applied at 2.5 t ha^{-1}, was found to foster significant improvements in the length of shoots, areas of leaves, plant biomass, volume of roots, and colonization of mycorrhiza in sorghum crops (Hameeda et al. 2007). The average increase of fresh biomass (over control treatment) of all treatments has been recorded to be 143%, 141%, and 204% in the years of 2014, 2015, and 2016, respectively. A high increase had the application of Sharjah-compost (233%) and low of 17% with Bontera™ application. The average increase of fresh biomass production from the spray was 137% (2015) and 146% (2016). Milošević et al. (2003), Mohammadi et al. (2012) reported beneficial effects on soil health and crop productivity with the application of biofertilizers and improvement in plant growth parameters (height and fresh biomass). Based on the results of this study, foliar spray of Bontera™ in all treatments had a significant average increase (172%) of fresh biomass over the control treatment. Soil properties in the cowpea plot improved with the application of ICBA-compost, Sharjah-compost, and Bontera™. Additionally, several years after the original application of these amendments ceased, residual effects have continued to present beneficial impacts on soil quality (Giniting et al. 2003), a finding also supported by the data collected in this study.

4.3.5 Grain Yield

4.3.5.1 Lablab-Bean

Grain yield of lablab-bean increased significantly in 2015 and 2016 when compared to that in 2014 in all the treatments including control (Fig. 4.8). However, the extent of increase differed with the treatments and was higher for Sharjah-compost. In 2016, grain yields reached 0.47 kg m^{-2}; yields were 0.11 and 0.44 kg m^{-2} in 2014 and 2015, respectively. Seed yield was higher between 2014 and 2015 as well. Sharma and Mitra (1990) reported the increase of grain and straw yield of rice with the application of organic materials. An improved yield of maize grain with the use of organic and inorganic fertilizers together has been reported by Dilshad et al.

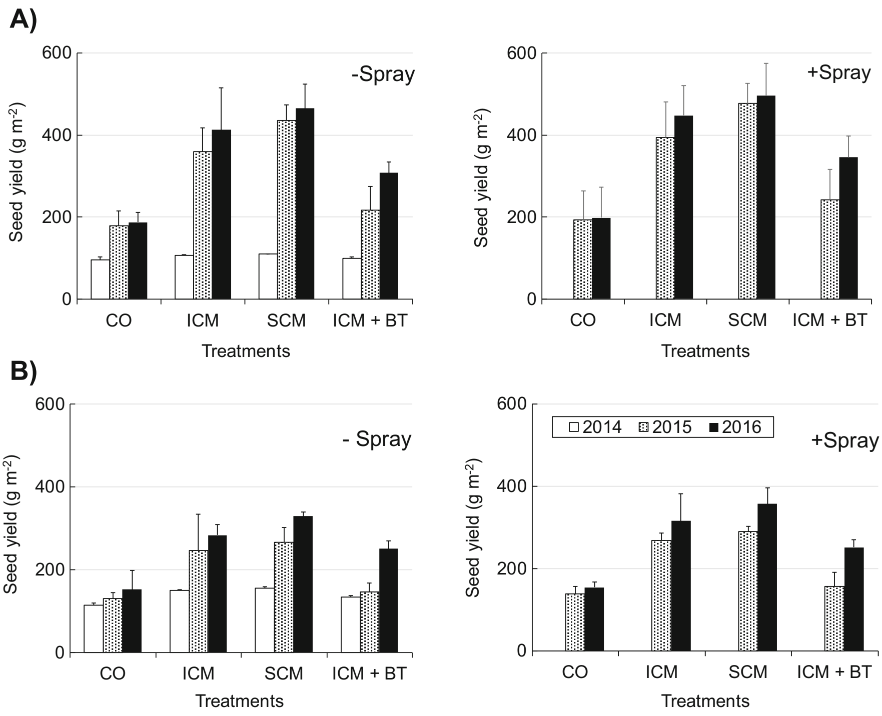

Fig. 4.8 Grain yield of (**a**) lablab-bean and (**b**) cowpea without (−spray) and with (+ spray) application of Bontera™ combined in treatments: CO, control; ICM, ICBA-compost; SCM, Sharjah-compost; and BT, Bontera™

(2010) as well. They further reported improved nutrient uptake when integrated nutrient management (including chemical fertilizers, organic fertilizers, and biofertilizers) was used, resulting in soil productivity enhancements. Incorporation of different combinations of organic materials, viz., farm yard manure and wheat residue, biofertilizer, and vermicomposting along with biofertilizers, has enhanced the grain yields by 51–58% (Davari and Sharma 2010). All characteristics of rice used to quantify the yields increased with the increasing rates of farm yard manure. Similarly, the application of organic manures and biofertilizers significantly influenced the growth, yield, and quality of crops (Singh et al. 2001). Surekha (2007) revealed that with the use of organic fertilizers over an extended period, there were gradual but discernible increases in grain yields. Comparable results were obtained by Badr et al. (2009). Regarding the interaction effect of organic fertilizer and biofertilizer on yield, Shoman et al. (2006) showed that yield was significantly affected by interaction between organic fertilizer and biofertilizer. With respect to response of seed yield to biofertilizer, data show that biofertilization (with *Bacillus polymyxa* known as *Paenibacillus polymyxa*) individually had a significant increase on seeds yield.

4.3.5.2 Cowpea

The grain yield of cowpea was higher in soil amended with Sharjah-compost in the 3 years under both sprayed and non-sprayed conditions (Fig. 4.8). However, higher grain yield was only obtained in 2016, and the yield was almost twice of that in 2015. Application of ICBA-compost and Bontera™ increased grain yield. It is to be noted that over the 2 years (2015 and 2016), the plant growth and soil health, when compared to control plots, improved due to soil temperatures that allowed the amelioration of the native soils. Plant growth is reported to have a positive effect on different soil health parameters.

Bontera™ applied in 2015 and 2016 through foliar spray was significantly beneficial to grain yields and had higher effect when it was applied in the soil. Grain yields of cowpea were lower than lablab-bean under all conditions to 2015 and 2016 under sprayed and non-sprayed conditions (Fig. 4.8).

Like biomass, the grain yield of lablab-bean was also greater than of cowpea in 2015 and 2016 years for all treatments when averaged. Ranganathan and Selvaseelan (1997) found a 20% increase of grain yield with the application of rice straw compost compared to farm yard manure and NPK fertilizer. Organic amendments increased grain yield by preserving soil organic carbon during the growing season in marginal environments. All measured variables presented significant differences between years. Additionally, annual climatic variations could have had considerable influences on plant growth and yield stability. Soil amendments had an insignificant effect on grain yield in 2014; however, in 2015 and 2016, yields were higher for plots with the three amendments. Bontera™ had a significant effect on yields, though, relative to the other two treatments, it was a smaller impact. This may be because no compost was applied during the first cropping season. The effect on lablab-bean was compared to that on cowpea.

Foliar application of Bontera™ had a positive impact on grain production. For two cropping years, i.e., 2015 and 2016 and the four soil treatments, it ranged between 5.6% and 12.6%. Higher spray impact was obtained for soil receiving Bontera™ and compost, i.e., 11.4% and 12.6% in 2015 and 2016, respectively. Singh et al. (1998) reported that the application of 7.5 t ha^{-1} farm yard manure produced significantly high grain yield and straw over unfertilized fields.

4.3.6 Soil Organic Carbon Content in Cultivated Soils

4.3.6.1 Lablab-Bean

Soil organic carbon increased significantly because of the use organic amendment (Fig. 4.5a). The increase was more pronounced in the plots that applied Sharjah-compost than ones with ICBA-compost in all 3 years. Organic matter content measured in the lablab soil root zone was higher in 2015 compared to 2014 and 2016 (Fig. 4.9). It may be attributed to different root zone characteristics and biological activity. In 2014, soil application of Bontera™ increased organic carbon content from 1.21 in 2014 to 1.34 g kg^{-1}. In the next 2 years, i.e., 2015 and 2016, the organic carbon content of soils given biofertilizer increased by almost 100% (Fig. 4.5a). This difference was due to the application of compost in 2015 and 2016, while no compost was applied in 2014 in biofertilizer plots. In control plots, the soil organic carbon content did not show a change in the 3 years. The addition of compost had increased quantity of humic acid and organic carbon content in sandy soils (Weber et al. 2007).

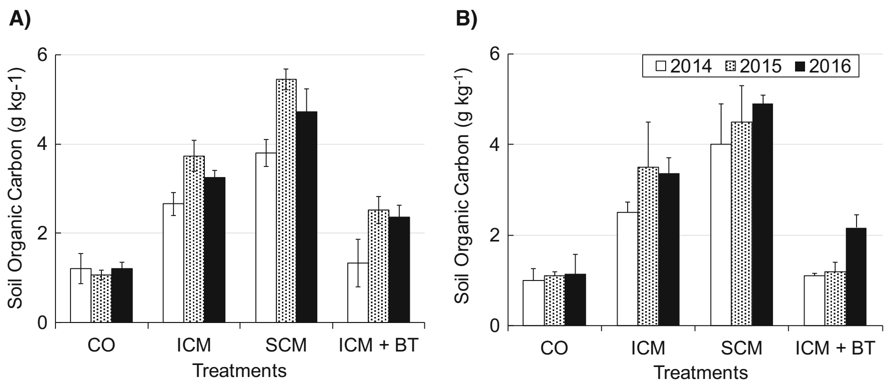

Fig. 4.9 Soil organic carbon content in (a) lablab-bean and (b) cowpea crop grown under treatments: CO, control; ICM, ICBA-compost; SCM, Sharjah-compost; and BT, Bontera™

4.3.6.2 Cowpea

One of the most significant positive effects attributed to the amendments was the increase of organic carbon content with the application of Sharjah-compost (299%, 309%, and 329% in the years 2014, 2015, and 2016, respectively, Fig. 4.9b). In contrast, plots that used the biofertilizer had low organic carbon (12% and 9% in 2014 and 2015, respectively). However, an increase of 90% was observed in the application of biofertilizer in combination with compost. Previous studies found that the soil is improved with the application of organic amendments which improved cowpeas and maize growth and yield (Rehman et al., 2010). In addition, these studies highlighted the beneficial effects of compost on the cowpea yield and nutrient content. Likewise, the application of organic manures and biofertilizers had significant effects on crop growth, yield, and quality. Dutta et al. (2003) reported a higher positive effect on microbial biomass and soil health because of the combinations of organic fertilizers and chemical fertilizers when compared to the addition of organic fertilizers alone.

Soil planted with lablab-bean had an average carbon content of 1.16, 3.21, 4.65, and 2.08 g kg^{-1} for the control, ICBA-compost, Sharjah-compost, and ICBA-compost + Bontera™, respectively, for the 3 years of study. Soil planted with lablab-bean had a similar difference due to soil treatments, i.e., the Sharjah-compost amendments increase soil carbon contents. This would suggest that Sharjah-compost has a higher proportion of relatively recalcitrant carbon as compared to ICBA-compost. It will be more valuable in enhancing organic matter content of the soil, while other composts with higher proportion of decomposable carbon can be advantageous, as they can release the acidic products of decomposition and impact the soil chemistry through the solubilization of calcium carbonate. Released calcium can replace sodium from the exchange complex allowing it to be less prevalent in the root zone. Differences in the extent of rhizodeposition by different plant types are well documented as is the impact of organic matter on Na/Ca relationships.

Figure 4.9 depicts the effects of soil amendment on soil organic matter content. A significant increase ($P > 0.05$) in soil organic matter content was observed over the period of 3 years that involved cropping with lablab-bean and cowpea. Higher organic matter content in the soil was a result of amendment with Sharjah-compost; this is due to its inherently higher content of organic matter, resulting in improved microbial activities. However, additional studies are required to substantiate this observation. Significant buildup of soil organic matter was observed over a period of 3 years, a finding that goes against the general notion that under relatively harsh conditions of temperature, organic matter is quickly lost. Nevertheless, the increase in organic matter is understandable following addition of animal manures, composts, etc., which is a finding corroborated by other studies (Meeuwissen 1992; Kaschl et al. 2002). There is a positive correlation between the addition of compost and biowaste and the buildup of soil organic matter. Indeed, the use of compost has been recommended to improve soil fertility for conventional and biological agricultural systems (Ouédraogo et al. 2001; Bonanomi et al. 2014).

The studies conducted between 2014 and 2016 highlighted the factors that influence and improve the buildup of organic matter, as well as the improvement of microbial activities and soil health in sandy soils. Dutta et al. (2003) reported that using organic fertilizers along with chemical fertilizers, when compared treatments that exclusively utilized organic fertilizers, had a higher positive effect on microbial biomass. Kaur et al. (2005) evaluated the ways that the chemical and biological properties were impacted in soils receiving farm yard manure (FYM), poultry manure, sugarcane filter cake alone, or chemical fertilizers alone or in which used a combination of biological and chemical fertilizers for 7 years under a cropping sequence of pearl millet and wheat. The results of all treatments (organic fertilizers) except chemical fertilizer application improved the status of key nutrients in the soil, particularly soil organic C, total N, P, and K. This study showed that balanced fertilization using both organic and chemical fertilizers is important for maintenance of SOM content and long-term soil productivity in the tropics where soil OM content is low. Ouédraogo et al. (2001) and Bonanomi et al. (2014) proposed the use of compost for conventional and biological agriculture systems to improve soil fertility to improve crop yield. Different crops have responded differently to various treatments (Fig. 4.5). In lablab-bean and cowpea, Sharjah-compost and ICBA-compost (2016) increased height of plant followed by integration of biofertilizer with compost (Fig. 4.6).

4.4 Conclusions

The feasibility of using of biochar to improve soil quality is evident from the increases in the amount of fresh biomass of quinoa, lablab-bean, and cowpea, as well as the increased accumulation of soil organic carbon content, which increased by 16–27% and 108–125%, respectively. Cation exchange capacity of soil increased to 34 and 49% with the application of 20 and 30 t ha^{-1} biochar, respectively.

In the field trial on quinoa, significant increase in fresh biomass of quinoa was 54% and 113% with the application of 20 and 30 t ha^{-1} of biochar, respectively. The soil organic matter (SOM) increased by 271–295%; cation exchange capacity of soil also increased by 36–52%, with the increase being more at higher rate of addition.

In the second experiment, two types of compost were used, ICBA-compost and Sharjah-compost. Both amendments present an environmentally friendly and economically viable option in agriculture fields to improve crop productivity. Organic waste is readily available, making it feasible for reuptake as reuse as a soil amendment; there is an additional environmental impact from its use, as the application of these composts spares them from entering landfills and thus reduces greenhouse gas emissions.

The combined use of ICBA-compost and Bontera™ has performed better than the recommended dose of inorganic fertilizers. Over 3 years of field trials, all organic amendments have shown general increase of plant growth parameters (height, fresh biomass, and grain yield) in all crops tested. However, a variable response was recorded, where the combined use of compost and biofertilizer has shown relatively better results than when biofertilizer was used alone. Organic amendments substantially increased the grain yield.

The addition of compost at the rate of 20 t ha^{-1} for 3 years on leguminous crops (lablab-bean and cowpea) has shown significant increases of soil organic matter. Moreover, our results suggest that biochar enhances SOM in a low fertility sandy soils that are commonly found in Dubai. These findings can be applied during the cultivation of both domestic and rentable crops, which are essential for small-scale farming activities.

Further studies in marginal environmental conditions are required to establish a relationship between the stable carbon fraction of composts and the buildup of soil organic matter, as well as to further study better ways to optimize the use of organic amendments in the context of integrated nutrient management.

The use of biochar from date palm waste is a promising amendment to improve sandy soil in desert agroecosystems. Nevertheless, other plant material and wastes should be used as well. Crop rotation, policultures, and mixed cropping systems should include biochar and composts to improve soil quality and crop productivity.

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References

Alandia G, Rodriguez JP, Jacobsen S-E, Bazile D, Condori B (2016) A new face of quinoa production: challenges for the Andean region. In: International conference quinoa for future food and nutrition security in marginal environments, December 6–8, 2016 Dubai, United Arab Emirates, ICBA. Dubai, ICBA, pp 29–30

Alshankiti A, Gill S (2016) Integrated plant nutrient management for sandy soil using chemical fertilizers, compost, biochar and biofertilizers—case study in UAE. J Arid Land Stud 26 (3):101–106. https://doi.org/10.14976/jals.26.3_101

Al-Wabel MI, Al-Omran A, El-Naggar AH, Nadeem M, Usman ARA (2013) Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. Bioresour Technol 131:374–379. https://doi.org/10.1016/j.biortech.2012.12.165

Anderson T (2012) Agrofuels and the myth of the marginal lands. The Gaia Foundation 2012:8

Badr EA, Ibrahim OM, El-Kramany MF (2009) Interaction effect of biological and organic fertilizers on yield and yield components of two wheat cultivars. Egyptian J Agronomy 31 (1):17–27

Benbi DK, Richter J (2003) Nitrogen dynamics. In: Benbi DK, Nieder R (eds) Handbook of processes and modelling in the soil-plant system. The Haworth Press, New York, pp 409–482

Bhargava A, Srivastava S (2017) Response of *Amaranthus sp.* to salinity stress: a review. In: Hirich A, Redouane C, Ragab R (eds) Emerging research in alternative crops under marginal environment. Springer, Netherlands

Bhargava A, Shukla S, Rajan S, Ohri D (2007) Genetic diversity for morphological and quality traits in quinoa (*Chenopodium quinoa* Willd.) germplasm. Genet Res Crop Evol 54:167–173. https://doi.org/10.1007/s10722-005-3011-0

Bonanomi G, Ascoli D, Scotti R, Gaglione R, Caceres SA, Sultana MG, Scelza S, Rao RMA, Zoina A (2014) Soil quality recovery and crop yield enhancement by combined application of compost and wood to vegetables grown under plastic tunnels. Agric Ecosyst Environ 192:1–7

Bruun EW, Hauggaard-Nielsen H, Norazana I, Egsgaard H, Ambus P, Jensen PA, Johansen KD (2011) Influence of fast pyrolysis temperature on biochar labile fraction and short-term carbon loss in a loamy soil. Biomass Bioenergy 35:1182–1189

Carter S, Shackley S, Sohi S, Suy TB, Haefele S (2013) The impact of biochar application on soil properties and plant growth of pot grown lettuce (*Lactuca sativa*) and cabbage (*Brassica chinensis*). Agronomy 3:404–418

Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S (2007) Agronomic values of greenwaste biochar as a soil amendment. Aust J Soil Res 45:629–634

Chan KY, Dorahy C, Wells T (2008) Use of garden organic compost in vegetable production under contrasting soil P status. Aust J Agric Res 59(4):374–382

Choukr-Allah R, Rao NK, Hirich A, Shahid M, Alshankiti A, Toderich K, Gill S, Butt KR (2016) Quinoa for marginal environments: toward future food and nutritional security in MENA and Central Asia regions. Front Plant Sci 7:346. https://doi.org/10.3389/fpls.2016.00346

Davari MR, Sharma SN (2010) Effect of different combinations of organic material and biofertilizers on productivity, grain quality and economics in organic farming of basmati rice (*Oryza sativa* L.). Indian J Agron 55:290–294

Deenik J, Diarra A, Uehara G, Campbell S, Sumiyoshi Y, Antal M Jr (2011) Charcoal ash and volatile matter effects on soil properties and plant growth in an acid Ultisol. Soil Sci 176:336–345

Dilshad MD, Lone MI, Jilani G, Malik MA, Yousaf M, Khalid R, Shamim F (2010) Integrated plant nutrient management (IPNM) on maize under rainfed condition. Pak J Nutr 9:896–901

Dutta S, Pal R, Chakeraborty A, Chakrabarti K (2003) Influence of integrated plant nutrient phosphorus and sugarcane and sugar yields. Field Crop Res 77:43–49

Economist Intelligence Unit (2010) The GCC in 2020-resources for the future. A report from the Economist Intelligence Unit-Sponsored by the Qatar Financial Centre Authority. The Economist Intelligence Unit (EIU), Geneva, Switzerland, 30p

Evans JP (2009) 21st century climate change in the Middle East. Climate Change 92(3–4):417–432

Gill S, Alshankiti A, Shahid SA (2016) Fate of composted and non-composted sewage sludge in sandy soil in terms of nitrogen mineralization and recovery of organic matter. Int J Adv Res Found 3(11):4–10

Giller KE (2001) Nitrogen fixation in tropical cropping systems, 2nd edn. CABI, Wallingford, 423pp

Giniting DA, Eghball B, Doran JW (2003) Greenhouse gas emission and soil indicators four years after manure and compost application. J Environ Qual 32:23–32

Haider G (2016) Biochar as a beneficial soil amendment in sandy soils. PhD Dissertation. Department of Plant Ecology, Faculty of Biology and Chemistry, Justus-Liebig-University Giessen, Germany, 142p

Hameeda B, Harini G, Rupela OP, Reddy G (2007) Effect of composts or vermicomposts on sorghum growth and mycorrhizal colonization. Afr J Biotechnol 6:9–12

Kaschl A, Romheld V, Chen Y (2002) The influence of soluble organic matter from municipal solid waste compost on trace metal leaching in calcareous soils. Sci Total Environ 291:45–57

Kaur K, Kapoor KK, Gupta AP (2005) Impact of organic manures with and without mineral fertilization on soil chemical and biological properties under tropical conditions. J Plant Nutr Soil Sci 168:117–122

Kirkpatrick EM (ed) (1983) Chambers 20th century dictionary. W & R Chambers Ltd, Edinburgh

Kwapinski W, Byrne CMP, Kryacho E, Wolfram P, Adley C, Leahy JJ, Novotny EH, Hayes MHB (2010) Biochar from biomass and waste. Waste Biomass Valor 1:177–189. https://doi.org/10.1007/s12649-010-9024-8

Laird DA, Martens DA, Kingery WL (2001) Nature of clay-humic complexes in an agricultural soil: I. Chemical, biological, and spectroscopic analyses. Soil Sci Soc Am J 65:1413–1418

Lehmann J, Joseph S (eds) (2009) Biochar for environmental management: science and technology. Earthscan, London

Lehmann J, Rondon M (2006) Biochar soil management on highly weathered soils in the humid tropics. In: Uphoff N (ed) Biological approaches to sustainable soil systems. CRC, Boca Raton, FL, pp 517–530

Lehmann J, da Silva Jr JP, Steiner C, Nehls T, Zech W, Glaser B (2003) Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil 249:343–357

Lian F, Xing B (2017) Black carbon (biochar) in water/soil environments: molecular structure, sorption, stability, and potential risk. Environ Sci Technol 51(23):13517–13532. https://doi.org/10.1021/acs.est.7b02528

Major J, Lehmann J, Rondon M, Goodale C (2010) Fate of soil-applied black carbon: downward migration, leaching and soil respiration. Glob Chang Biol 16:1366–1379

Meeuwissen PC (1992) Champost can good concurrent met mestsoorten. De champignon cultur 36 (2):95–101

Mekuria M, Waddington SR (2002) Initiatives to encourage farmer adoption of soil fertility technologies for maize-based cropping systems in southern Africa. In: Barrett CB, Place F, Aboud AA (eds) Natural resources management in African Agriculture: understanding and improving current practices. CAB International, Wallingford, UK, pp 219–233

Milosevic N, Govedarica M, Jelicic Z, Protic R, Kuzevski J, Krstanovic S (2003) Microbial inoculants as biofertilizers: testing, potential, and important factor for sustainable agriculture. In: Komnenic V (ed) Proceedings of scientific papers of institute of PKB Agroekonomik, vol 9. PKB Agroekonomik, Belgrade, Serbia, pp 89–98

Mohammadi K, Sohrabi Y, Heidari G, Khalesro K, Majid M (2012) Effective factors on biological nitrogen fixation. Afr J Agric Res 7(12):1782–1788

Mpepereki S, Javaheri F, Davis P, Giller KE (2000) Soybeans and sustainable agriculture; promiscuous soybeans in southern Africa. Field Crop Res 65:137–149

Nyamangara J, Bergstrom LF, Piha MI, Giller KE (2003) Fertilizer use efficiency and nitrate leaching in a tropical sandy soil. J Environ Qual 32:599–606

Ouédraogo E, Mando A, Zombré NP (2001) Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa. Agric Ecosyst Environ 84:259–266

Ouyang L, Wang F, Tang J, Yu L, Zhang R (2013) Effects of biochar amendment on soil aggregates and hydraulic properties. J Soil Sci Plant Nutr 13:991–1002

Pérez-Piqueres A, Edel-Hermann V, Alabouvette C, Steinberg C (2006) Response of soil microbial communities to compost amendments. Soil Biol Biochem 38:460–470

Postma J, Montanari M, Van den Boogert PHJF (2003) Microbial enrichment to enhance the disease suppressive activity of compost. Eur J Soil Biol 39:157–163

Prota L (2006) Céréales et légumes secs Fondation PROTA/Backhuys publishen/CTA Klageningen, (Ressources Végétales De L'Afrique Tropicale1) Pays-Bas. pp 250–258

Rahman KM, Molla AH, Rahman MA (2006) Feasibility of sustainable recycling of municipal solid waste as organic fertilizer for plant growth and development. The Agriculturists 4:7–14

Ranganathan DS, Selvaseelan DA (1997) Mushroom spent rice straw compost and composted coir pith as organic manures for rice. J Indian Soc Soil Sci 45(3):510–514

Rao NK (2013) Crop wild relatives from the Arabian peninsula. Genet Resour Crop Evol 60:1709–1725. https://doi.org/10.1007/s10722-013-9972-5

Rao NK, Shahid M (2012) Quinoa – a promising new crop for the Arabian Peninsula. American-Eurasian. J Agric Environ Sci 12(10):1350–1355. https://doi.org/10.5829/idosi.aejaes.2012.12.10.1823

Rao NK, Dakheel A (2015) Manual of seed production of salt tolerant crops. International Center for Biosaline Agriculture. ICBA, Dubai, 120p

Rao NK, Shahid M (2011) Potential of cowpea (*Vigna unguiculata* (L.) Walp.) and guar (*Cyamopsis tetragonoloba* (L.) Taub.) as alternative forage legumes for the United Arab Emirates. Emir J Food Agric 23(2):147–156

Rao NK, Shahid M, Shahid SA (2009) Alternative crops for diversifying production systems in the Arabian peninsula. Arab Gulf J Scientific Res 27(4):195–203

Rehman HU, Ali A, Waseem M, Tanveer A, Tahir M, Nadeem MA, Zamir MSI (2010) Impact of nitrogen application on growth and yield of maize (*Zea mays* L.) grown alone and in combination cowpea (*Vigna unguiculata* L.). Am Eurasian J Agric Environ Sci 7:43–47

Rodd V, Warman PR, Hickelton P, Webb K (2002) Comparison of N-fertilizer, source-separated municipal solid waste compost and semi-solid beef manure on the nutrient concentration in boot-stage barley and wheat tissue. Can J Soil Sci 82:33. https://doi.org/10.4141/S00-055

Rodriguez JP, Andreasen C, Sørensen M, Jacobsen S-E (2020a) Cañahua (*Chenopodium pallidicaule*)—a promising new crop for arid areas. In: Hirich A, Choukr-Allah R, Ragab R (eds) Emerging research in alternative crops under marginal environment. Springer, Netherlands

Rodriguez JP, Ono E, Al Mousa's AI, Choukr-Allah R, Hirich A (2020b) Cultivation of quinoa (Chenopodium quinoa) in desert ecoregion. In: Hirich A, Choukr-Allah R, Ragab R (eds) Emerging research in alternative crops under marginal environment. Springer, Netherlands

Sakala WD, Cadisch G, Giller KE (2000) Interaction between residues of maize and pigeon pea and mineral N fertilizer during decomposition and N-mineralization. Soil Boil Biochem 32:679–688

Schlick G, Bubenheim DL (1996) Quinoa: candidate crop for NASA's controlled ecological life support systems. In: Janick J (ed) New crops. ASHS Press, Arlington, VA, pp 632–640

Shahid SA, Alshankiti A (2013) Sustainable food production in marginal lands – case study GDLA member countries. Int Soil Water Conserv Res 1(1):24–38

Shahid SA, Abdelfattah MA, Taha FK (eds) (2013) Developments in soil salinity assessment and reclamation- innovative thinking and use of marginal soil and water resources in irrigated agriculture. Springer, Dordrecht, 808 p. https://doi.org/10.1007/978-94-007-5684-7

Sharma AR, Mitra BN (1990) Complementary effect of organic material in rice-wheat crop sequence. Indian J Agric Sci 60(3):163–168

Sharma SR, Rao NK, Gokhale TS, Shoaib I (2013) Isolation and characterization of salt-tolerant rizhobia native to the desert soils of United Arab Emirates. Emir J Food Agric 25(2):102–108. https://doi.org/10.9755/ejfa.v25i2.7590

Shoman HA, Abo-Shtaia AM, El-Shouny KA, Abd El-Gawad MA (2006) Effect of biological and organic fertilization on yield and its components of two wheat cultivars under Al-Wady Al Gadeed conditions. Alexandria J Agric Res 51:49–65

Singh G, Singh OP, Yadava RA, Singh PP, Nayak R (1998) Response of rice (*Oryza sativa*) varieties to nitrogen levels in flash flood conditions. Indian J Agron 43(3):506–510

Singh KN, Prasad B, Sinha SK (2001) Effect of integrated nutrient management on a Typic Haplaquant on yield and nutrient availability in a rice-wheat cropping system. Aust J Agric Res 52(8):855–858

Steiner C, Teixeira W, Lehmann J, Nehls T, Vasconcelos de Macêdo J, Blum W, Zech W (2007) Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291:1–2

Steiner C, Glaser B, Teixeira WG, Lehmann J, Blum WEH, Zech W (2008) Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. J Plant Nutr Soil Sci 171:893–899

Sullivan DM, Bary AI, Thomas DR, Fransen SC, Cogger CG (2002) Food waste compost effects on fertilizer nitrogen deficiency, available nitrogen and tall fescue yield. Soil Sci Soc of Am J 66:154–161

Surekha K (2007) Nitrogen-release pattern from organic sources of different C: N ratios and lignin content, and their contribution to irrigated rice (*Oryza sativa*). Indian J Agron 52(3):220–224

Usman ARA, Abuldjabbar A, Vithanage M, Ok YS, Ahmad M, Ahmad M, Elfaki J, Abdulazeem SS, Al-Wabel MI (2015) Biochar productions from date palm waste: charring temperature induced changes in composition and surface chemistry. J Anal Appl Pyrolysis 115:392–400. https://doi.org/10.1016/j.jaap.2015.08.016

VanZwieten L, Kimber S, Morris S, Chan KY, Downie A, Rust J, Joseph S, Cowie A (2010) Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant Soil 327:235–246. https://doi.org/10.1007/s11104-009-0050-x

Weber J, Karczewska A, Drozd J, Licznar S, Jamroz E, Kocowicz A (2007) Agricultural and ecological aspects of a sandy soil as affected by the application of municipal solid waste composts. Soil Biol Biochem 39(6):1294–1302

Willer H, Lernoud J (2017) The world of organic agriculture. Statistics and emerging trends 2017. Bonn, Research Institute of Organic Agriculture (FiBL), Frick, and IFOAM - Organics International

World Integrated Trade Solution (2014) United Arab Emirates Food Products Imports in 2014. World Integrated Trade Solution (WITS). Consulted 20 July 2017, http://wits.worldbank.org/CountryProfile/en/Country/ARE/Year/2014/TradeFlow/Import/Partner/all/Product/16-24_FoodProd

Zech W, Senesi N, Guggenberger G, Kaiser K, Lehmann J, Miano TM, Miltner A, Schroth G (1997) Factors controlling humification and mineralization of soil organic matter in the tropics. Geoderma 79:117–161. https://doi.org/10.1016/S0016-7061(97)00040-2

Zhai W, Peebles ED, Mejia L, Zumwalt CD, Corzo A (2014) Effects of dietary amino acid density and metabolizable energy level on the growth and meat yield of summer-reared broilers. J Appl Poult Res 23:501–515. https://doi.org/10.3382/japr.2014-00961

Zhang W, Ahanbieke P, Wang BJ, Xu WL, Li LH, Christie P, Li L (2013) Root distribution and interactions in jujube tree/wheat agroforestry system. Agrofor Syst 87:929–939. https://doi.org/10.1007/s10457-013-9609-x

Zhang Y, Idowu OJ, Brewer E (2016) Using agricultural residue biochar to improve soil quality of desert soils. Agriculture 6:10. https://doi.org/10.3390/agriculture6010010

Chapter 5
The Extraordinary Salt Tolerance of Quinoa

Shahid Iqbal, Shahzad M. A. Basra, Muhammad Sohail Saddiq, Aizheng Yang, Saqib Saleem Akhtar, and Sven-Erik Jacobsen

Abstract Escalating salinization due to natural and anthropogenic activities is a major threat to sustainability of agriculture over the world. In this situation quinoa can be a good option for salt-affected soils. It is a facultative halophyte which can tolerate salinity levels up to the level of sea water. Due to these characters, interest to grow this crop has increased exponentially in recent years over the globe, and many studies have been conducted to elucidate salt-tolerance mechanisms and to explore growth performance and seed quality under various salt regimes. It seems that quinoa manages excessive Na^+ loads efficiently by sequestering it in leaf vacuoles and translocating it to older leaves; it has a good antioxidative defense system, better K^+ uptake and retention, and unique modulations in stomatal density and characters. Furthermore, it has been observed that its growth and yield improves at moderate salt regimes, even with higher amounts of protein and some minerals. These characteristics offer opportunities that quinoa can be explored in arid and semiarid regions where crop production of various major crops is severely affected by escalated soil salinization.

Keywords Halophyte · *Chenopodium quinoa* · Food security

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5.1 Introduction

Increasing soil salinity is a major cause of soil degradation over the world; at present 7% is salt-affected (Panta et al. 2014). Weathering of rocks (primary salinization) as well as anthropogenic activities (secondary salinization) causes increased concentration of soluble salts (Ghassemi et al. 1995). Secondary salinization is aggravated by frequent use of underground brackish water and contaminated sewage water for irrigation purposes and clearance of forest lands for crop production and pastures (Barret-Lennard 2002). Combined natural and human-induced salt-contaminated soils are estimated to 960 million ha (Wicke et al. 2011). Approximately, 100 million ha productive land have turned saline due to use of saline underground water for irrigation purposes, equating about 11% of the world's irrigated land (FAO 2012). 15% of cultivated land is irrigated, contributing significantly to salinization (Munns 2005). The extent of salt-affected land and its spread are highest and continuous in the most economically challenged and populated countries, i.e., Bangladesh (1 million ha; Hossain 2010), Pakistan (6 million ha; Vashev et al. 2010), and India (7 million ha; Vashev et al. 2010), posing severe threats to sustainability of agriculture. To be able to produce on salt-affected soils and eventually reduce salinity, the use of halophytes is an option. One of these halophytes is quinoa (*Chenopodium quinoa* Willd.), which is more salt tolerant than other crops (Razzaghi et al. 2015). It was shown that the percentage of leaf area covered by stomata and stomatal conductance was lower in salt-treated plants, as a salt-tolerance mechanism (Becker et al. 2017). Some quinoa genotypes tolerate salinity up to 40 dS m^{-1} (Adolf et al. 2013).

When comparing the halophyte quinoa with a glycophyte pea, it was shown that salinity tolerance in quinoa is achieved by a faster removal of Na^+ from the cytosol and a high K^+ concentration in roots and shoots under salinity, resulting in a high K^+/Na^+ ratio, and that this mechanism is driven by a higher proton pump activity, compared with glycophytic pea species (Sun et al. 2017).

Quinoa originates from the Andes of South America, where for more than seven thousand years it has produced edible seeds and leaves. Quinoa belongs to the Amaranthaceae family which contains many halophytic species. There is a rapidly increasing interest in quinoa worldwide (Bazile et al. 2016), due to its stress tolerance and its high nutritional quality with a high content of essential amino acids (Dini et al. 2005), minerals (Fe, Cu, Ca, Mg, and Zn), and vitamins (B2, A, E) (Repo-Carrasco et al. 2003).

Here we will present up-to-date information about quinoa's salt tolerance and its performance at different salt regimes. We will discuss the morphological, physiological, and molecular effects of salinity stress. The gathered knowledge will be helpful for its adaptation to new environments and for future breeding programs for the further improvement of salt tolerance in quinoa in order to develop salt-tolerant cultivars. Quinoa has been suggested as a model crop for salinity tolerance (Ruiz et al. 2016), but much more studies are needed to determine its performance under natural salt-affected agroecological conditions.

5.2 Quinoa Growth Performance Under Salinity

5.2.1 Seedling Establishment

Plant establishment is a critical growth phase of a plant's life cycle especially when seeds are small and sown under stress conditions. Halophytes are tolerant to salts but not necessarily at germination (Debez et al. 2004). Some halophytes, including quinoa, are affected by salts during seed germination and seedling emergence stages (Tobe et al. 2000; Malcolm et al. 2003). The critical time in quinoa phenology is stand establishment (Iqbal 2019). Gómez-Pando et al. (2010) explored variations in germination percentage of quinoa germplasm (182 quinoa accessions) under saline regimes (250 mM saline water) depending on their genetic variability and resistance to salt stress. Jacobsen et al. (2003) reported that the Peruvian quinoa cultivar Kancolla seed had 75% germination ability at 57 dS m^{-1} salt stress level. Higher concentrations of salts affected seedling establishment, biomass, and growth (Ruiz-Carrasco et al. 2011). High salt tolerance of quinoa at germination stage was due to replacement of toxic ions (Na^{+} and Cl^{-}) with compatible ions, i.e., K^{+}, Ca^{+}, Mg^{+2}, SO_4^{+2}, and PO_4^{+3}. Quinoa tolerates high salts due to more protective seed interior (Koyro and Eisa 2008) and Na^{+} exclusion (Hariadi et al. 2011). In general, morphological and physiological characteristics contribute to a high salt tolerance in quinoa which is also cultivar depending.

5.2.2 Growth and Yield Performance

Quinoa grows on salt flats of the altiplano located in Bolivia and saline coastal soils of Chile. Most experiments confirmed the halophytic behavior of quinoa (Hariadi et al. 2011), as salinity promotes growth of quinoa up to a certain limit. Quinoa cv. Titicaca was grown on six salinity levels up to 70 days, where significant negative impact on seed germination was observed at 80% of sea level salinity, while maximum growth was recorded between 20 and 40% of sea water salinity. In another study quinoa yield was highest at intermediate saline regimes (10–20 dS m^{-1}) (Jacobsen et al. 2003). At a salt concentration of 25 dS m^{-1}, yield was reduced to 50%, but even under such high salt concentration, quinoa has the ability to grow and yield until 51.5 dS m^{-1}(Razzaghi et al. 2015).

Relative salinity tolerance was studied by Maas and Hoffman (1977) of crops based on two criteria (a) the maximal salinity level without yield reduction and (b) the percent yield decreases per unit salinity increase beyond this threshold. Classification was made based on qualitative tolerance variations to electrical conductance values, and rating was done between tolerant (T) (EC; 24–32 dS m^{-1}), moderately tolerant (MT) (EC: 16–24 dS m^{-1}), moderately sensitive (MS) (EC: 8–16 dS m^{-1}), or sensitive (S) (EC: 0–8 dS m^{-1}). Qadir et al. (2007) explained the yield potential of crops as a function of rhizosphere salinity from calculation of data

Table 5.1 Variation in salinity tolerance of quinoa genotypes

Genotype	Origin	EC (dS m^{-1})	YR[a] (%)	References
407	USA	6.5[b]	18	Karyotis et al. (2003)
Colorado 407D (PI 596293)	Chile	32[c]	65	Peterson and Murphy (2015)
UDEC-1 (PI 634923)	Chile	32[c]	43	Peterson and Murphy (2015)
Baer (PI 634918)	Chile	32[c]	49	Peterson and Murphy (2015)
QQ065 (PI614880)	Chile	32[c]	73	Peterson and Murphy (2015)
Titicaca	Denmark	20[d]	3.7	Yazar et al. (2015)
Titicaca	Denmark	22[d]	17	Pulvento et al. (2010, 2012)
Titicaca	Denmark	40[c]	85	Yang et al. (2016)
D0708	NA	10[c]	9	Hirich et al. (2014)
D0708	NA	20[c]	24	Hirich et al. (2014)
D0708	NA	30[c]	34	Hirich et al. (2014)

[a]YR: Yield reduction, %
[b]EC of natural saline-sodic field
[c]EC developed in pots, placed in greenhouse using NaCl; NA means not available
[d]EC developed in open field using salt mixture

provided by Maas and Grattan (1999). They recorded the EC50 ranges (the EC of soil responsible for 50% yield reduction) for several crops. Razzaghi et al. (2011b) calculated the value for quinoa to be 24 dS m^{-1}, which classifies quinoa as a highly salt-tolerant species.

Pulvento et al. (2012) tested quinoa in field conditions during 2009–2010 in Southern Italy in order to explore the influence of salt stress by measuring quantitative and qualitative traits. Quinoa field plots were irrigated with normal and saline water, where saline water created a salt level of 22 dS m^{-1} in soil. Salt stress did not reduce yield and even increased seed weight, fiber, and total saponin content in seeds. Variations in yield under salt stress are observed (Table 5.1).

5.3 Salt-Tolerance Mechanisms

Glycophyte (salt-sensitive) and halophyte (salt-tolerant) species have similar types of anatomy and physiology, but halophytes exhibit unique salt-tolerance mechanisms (Shabala and Mackay 2011). The question is if quinoa displays exceptional strategies to adapt and complete its life span under high salt stress?

5.3.1 Morphological Characters

5.3.1.1 Seed Characteristics

Many experiments show that halophytes may be salt-sensitive during seed germination and emergence of seedlings against salt stress (Debez et al. 2004). The physiological mechanisms of sequestration of sodium ions into the vacuole depend on ion homeostasis, distribution, and levels of other ions, in seeds and other tissues (Hasegawa et al. 2000). These mechanisms do not affect seed viability. Organic constituents (mainly $(CH_2O)_x$ and other carbon-comprising compounds) of quinoa decreased at high NaCl concentrations. Even with an increase of sodium ions, the K^+/Na^+ ratio was never observed lower than 1. Hence, buildup of K^+ ions and other vital nutrients, such as phosphorus and sulfur, even at higher salinity, was stable. The route of toxic cytoplasmic Na^+ and Cl^- to the inner parts of seeds is reduced by the testa. Seeds of quinoa grown under salt stress provide a vital tolerance strategy related to compacted seed testa with perisperm, providing defensive barriers ensuring the elimination of toxic Na^+ and Cl^-, thus regulating the ratio of K^+/Na^+ inside the seed. Seed viability is also dependent on the capacity of Na^+ exclusion (Hariadi et al. 2011).

5.3.1.2 Leaf Salt Bladders

Leaves of halophytes have salt bladders, glands, or trichomes (Fig. 5.1). Accumulation and sequestration of toxic salts into these special anatomical structures seems to be an efficient strategy to salt tolerance in quinoa (Agarie et al. 2007). These

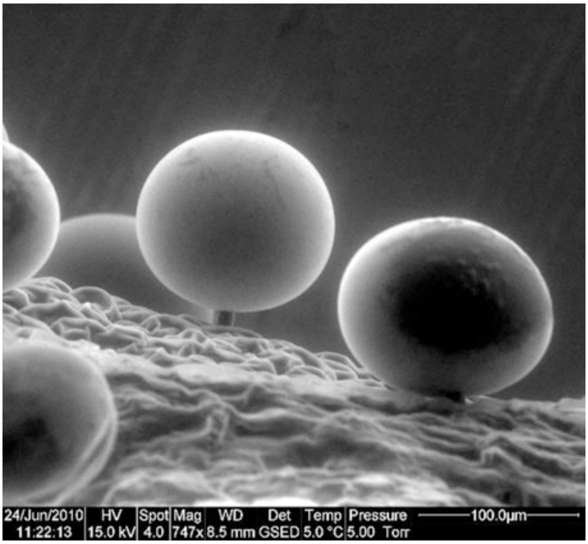

Fig. 5.1 Micrograph of the salt bladders of a young leaf of quinoa

structures are mainly involved in compartmentalization of incompatible ions, and thus these ions were excluded from primary photosynthetic active mesophyll and other parts of the plant. The ions may prove themselves to be beneficial in osmoprotection and act as a second epidermis, thereby protecting photosynthetic machinery from UV-induced injury.

In the salt-tolerant species *Mesembryanthemum crystallinum*, the epidermal bladder cells (EBCs) were able to accumulate water and metabolites like malate, cysteine, inositol, pinitol, and flavonoids (Agarie et al. 2007; Jou et al. 2007). Therefore, accumulation of these compounds having chaperone ability in EBCs displays a protective role from ROS attack. The accumulation of calcium oxalate crystals in leaves of quinoa was linked to elevated Ca^{2+} under salt stress (Riccardi et al. 2014). In a Chilean germplasm of quinoa (BO78), negligible changes in EBC numbers were recorded under salinity, so restricting ion accumulation may not be controlled by EBCs (Orsini et al. 2011).

5.3.1.3 Stomata

Transpiration rate is decreased under excessive amount of salts. The decline in stomatal conductance of gases in leaves of halophytes is assumed to be a vital parameter for improved water use efficiency under stress conditions. These adaptive responses may occur through morphological changes, e.g., decreases in size and densities of stomata, or through physiological regulation of stomatal aperture in response to ABA. Under saline conditions, a reduction of 50% in stomatal density followed by decreased size of stomata has been described in the salt-sensitive Chilean accession BO78 (Orsini et al. 2011). In another study, 14 quinoa lines were examined for salt tolerance, where reduced stomatal densities were observed in all lines under saline regimes (Shabala et al. 2013).

5.3.2 Physiological Mechanisms

5.3.2.1 Na^+ Uptake and Transport

Salinity tolerance has been widely linked with reduced Na^+ uptake. By using a mixed salt solution, a three- to fourfold increase in sodium was observed in upper parts of plants (Wilson et al. 2002), whereas in wheat, sodium concentration increased more than sixfold. Variations in quinoa germplasm regarding salinity tolerance were directly linked to Na^+ uptake, as highly tolerant genotypes exhibited low levels of Na^+ in the xylem (Shabala et al. 2013). The 14 genotypes could be categorized in to two groups, that is, Na^+ excluders or includers, with the most salt-tolerant ones being excluders. A quick uptake of Na^+ in the leaves is mandatory for osmotic adjustment, as ion toxicity is avoided in most genotypes of quinoa by controlling Na^+ charging into the xylem sap. Generally, Na^+ exclusion is thought of as a beneficial attribute in non-halophytes (Munns and Tester 2008).

In *Arabidopsis*, Na^+ exclusion is mediated by Na^+/H^+ exchangers operative at the plasma membrane of epidermal root cells (Blumwald et al. 2000) encoded by the salt overly sensitive (SOS1) gene (Qiu et al. 2002). In quinoa, SOS1 gene expression of salt-stressed plants has been identified (Maughan et al. 2009; Ruiz- Carrasco et al. 2011). Bonales-Alatorre et al. (2013) examined the activities of vacuolar and plasma membrane channels and observed the genotypic variation regarding several mechanistic processes associated with salt tolerance. Salt-sensitive cv. Q52206 and salt-tolerant cv. Q16 of quinoa were compared, and a significantly enhanced Na^+ exclusion rate was observed in mesophyll cells of leaf, keeping low Na^+ concentrations in cytosol and decreased activity of vacuolar channels, improved K^+ maintenance in the mesophyll cells of leaf, and enhanced activity of H^+ pumps permitting mesophyll cells for quick reestablishment of membrane potential. These mechanisms are highly linked in salinity tolerance of quinoa. The tonoplast potential was linked with sodium movement out of the vacuole. Fast channels of vacuole (FV) were found inactive in older leaves of stressed plants, whereas FV conductance in juvenile leaves increased in similar saline regimes and was at least twofold higher, representing the total Na^+ in the mesophyll cells of leaves. Additionally, under saline regimes, a sevenfold increase in the number of slow vacuolar pathways (SV) was observed in juvenile leaves (having less Na^+), which shows that quinoa has the capability to adjust the activities of FV and SV channels. This was seen from the considerable amount of Na^+ which was compartmentalized in the vacuoles of aged leaves, thus shielding new emerging leaves from extreme Na^+ buildups. This unique mechanism of Na^+ compartmentation has been observed and elaborated in many halophytes as a central component of salt tolerance (Munns et al. 2006).

5.3.2.2 Ion Homeostasis and Compartmentalization

Maintaining ion homeostasis by ion uptake and compartmentalization is not only crucial for normal plant growth but is also an essential process for growth during salt stress. Irrespective of their nature, neither glycophytes nor halophytes can tolerate high salt concentration in their cytoplasm. Hence, the excess salt is either transported to the vacuole or sequestered in older tissues which eventually are sacrificed, thereby protecting the plant from salinity stress. Extremely saline conditions can cause ion toxicity because of Na^+ and Cl^- buildup (Munns and Tester 2008). Some glycophytes limit movement of incompatible ions toward the shoot, by restricting influx of ion at root, thus avoiding ion toxicity. Halophytes take up ions and transfer and accumulate them in plant's aboveground parts (Flowers and Colmer 2008).

Water uptake and transport may be facilitated by osmotic adjustment resulting from the accumulation of inorganic ions like sodium, potassium, and chloride, with lower metabolic energy cost essential for the organic osmolyte biosynthesis. In quinoa cv. Titicaca with NaCl levels ranging from 0 to 500 mM, Hariadi et al. (2011) showed that cell turgor was maintained from uptake of K^+ and Na^+ ions. Up to 95% of cell turgor in old leaves and 80–100% of turgor in cells of juvenile leaves were due to K^+ and Na^+ accumulation. High buildup of Na^+ was also recorded in cv. BO78, when grown in NaCl levels ranging from 150 to 750 mM (Orsini et al. 2011). In non-tolerant plants, salt stress usually triggered K^+ efflux, reduced uptake of K^+, and a consequential drop of K^+ level in the cell which may be very harmful (Demidchik et al. 2010).

Therefore, K^+ homeostasis is a crucial aspect of salt tolerance, and the capability to maintain an optimum K^+/Na^+ ratio is thought to be vital for tolerance to salt stress (Munns and Tester 2008). Suhayda et al. (1992) explored a strong association between leaf tissue K^+/Na^+ ratio and salt tolerance in barley and recommended that this attribute could be used as screening criterion for the identification of salt-tolerant genotypes.

Wilson et al. (2002) evaluated salinity tolerance and ion buildup in wheat and quinoa against mixed salt stress (combinations of NaCl, $MgSO_4$, $CaCl_2$, and Na_2SO_4) using Andean hybrid quinoa cv. and wheat cv. Yecora Rojo. There was no significant drop in leaf area, plant height, and dry weight at salt concentrations of 11 dS m^{-1}, equal to 110 mM, in quinoa, but in wheat increasing salt stress caused marked reduction in K^+/Na^+ ratios of leaves and stem, and this decline was much higher in wheat. In the salt-sensitive cv. BO78, the increased buildup of Na^+ at 150 mM NaCl was the cause of a decline in the ratio K^+/Na^+. However, when NaCl levels were raised to 600 mM, plants displayed a threefold increased concentration of K^+ as compared to control plants (Orsini et al. 2011). Turgor adjustment is an important mechanism of inorganic ions and has been recorded in various halophytes (Inan et al. 2004). The documented improved values of K^+ concentration in leaf sap of juvenile leaves of quinoa (e.g., 400–650 mM) are consistent with the study of Hariadi et al. (2011). In another detailed study, salt stress modulated more uptake of Na^+ and K^+ up to 100 and 60 kg ha^{-1}, respectively (Razzaghi et al. 2015). So, it is concluded that quinoa keeps effective homeostatic mechanisms related to K^+ retention and osmotic adjustment, improving salt tolerance.

5.3.2.3 Gas Exchange Relations

Abscisic acid regulates the stomatal pore opening and closing by the outward and inward flux of inorganic ions in guard cells. Salinity which caused drought stress symptoms may lead to increase in ABA, reduced foliage, and decreased soil water potential (Ψ_w).

Salinity is known to result in declined gas exchange (Iqbal et al. 2017). Razzaghi et al. (2011a) reported that with an increase in NaCl level, there was seen a reduction in soil Ψ_w which ultimately decreased leaf Ψ_w and gaseous exchange in leaves of quinoa even if they were irrigated thoroughly. Orsini et al. (2011) demonstrated 50–60% reduction in gaseous exchange in a salt-susceptible cultivar (BO78) under medium (150 mM) to high (300 mM) NaCl stress. Reduced gaseous exchange through stomata limits water uptake by limiting transpiration; however, at the same time, it lowers CO_2 uptake (Iyengar and Reddy 1997). Two distinct cultivars

(Titicaca and Utusaya) of quinoa were analyzed for stomatal conductance and photosynthetic carbon dioxide assimilation under salt stress. Utusaya, which originates from the Bolivian salt desert, was least affected, with just 25% decrease in total CO_2 fixation as compared to almost 75% in cv. Titicaca (Adolf et al. 2013). Gaseous exchange declined in Utusaya cultivar even under control conditions, and it was conceived as a plausible tradeoff between tolerance under stress and yield. Regardless of the impacts of high salt stress on carbon dioxide entry from stomatal opening and assimilation, numerous records entail the unaffected maximum photochemical efficacy of photosystem II (Adolf et al. 2013). However, more research is required to be done on the fact that photosystem II is not a chief target of salt stress (Adolf et al. 2012).

5.3.2.4 Compatible Solutes

Different researchers have reported an increase in organic and inorganic compatible solutes, mainly glycine betaine, proline, K^+, etc. (Shabala and Mackay 2011). The buildup of these osmolytes or solutes is mandatory for sustaining turgor pressure of cell which enables cell expansion under increased osmolality; however the role of organic vs inorganic solute contribution to stress tolerance is a debated topic as observed by Hasegawa et al. (2000). The accumulation of organic solutes occurs even when there is high buildup of inorganic solutes.

Four main groups of organic osmolytes are identified, i.e., sugars, polyols, quaternary amines, and amino acids. All of them have been reported in tissues of quinoa (Aguilar et al. 2003; Ruffino et al. 2010; Orsini et al. 2011; Ruiz-Carrasco et al. 2011). Morales et al. (2011) observed minor quantities of proline, sorbitol, and pinitol and huge quantities of betaine, trehalose, and particular trigonelline in cvs. Ollague and Chipaya.

The response of young plants to high salinity with respect to carbohydrate metabolism indicates an ability of quinoa to adjust osmotically to a saline environment in its juvenile stage of development. Prado et al. (2000) found modulations in leaf glucose, sucrose, and fructose content in normal and salt-stressed seedlings of quinoa cv. Sajama at low-temperature regimes.

Tissues of embryo of two quinoa accessions from sea level (Baer) and altiplano (Sajama) were analyzed with Western blot analysis, revealing the existence of multiple bands of dehydrins in both, but the quantity of bands, i.e., 32 and 30 kDa, varied (Carjuzaa et al. 2008). It was concluded that many dehydrins are constitutive, and some of those may be linked with adaption to various environments. In another analysis, Burrieza et al. (2012) examined the influence of salts on configuration of dehydrins in mature embryos of cultivar Hualhuas. They showed that under saline and arid conditions of the altiplano, at least four dehydrin types were detected (using Western blot method) in seed harvested from normal and salt-grown plants. In salt-treated plants, no supplementary bands were recorded, and only one band of 30 kDa was amplified under 300 and 500 mM NaCl concentration. The roles and localizations of dehydrins might depend upon the phosphorylation of isoforms of salts. Under NaCl stress, high contents of trigonelline (0.87 m mol g^{-1} dry weight) aggregated in leaves as well as roots. This concentration far surpassed those that were recorded in other plants like corn, soybean, and tomato.

5.3.2.5 Osmoprotectants

Amino acid proline accumulation under various salt regimes has been found to function as compatible osmolyte, as osmoprotectant shielding subcellular structures and macromolecules, and as signaling (Szabados and Savoure 2010). Elevated proline levels were recorded in shoots of salt-stressed quinoa. At sea level salinity, the increase of proline was ten times higher as compared to non-saline control (Orsini et al. 2011). Lowered concentration range of total leaf proline (0.4–0.9 mg g^{-1} fresh weight) was recorded by Aguilar et al. (2003) in quinoa accessions from Peru from different environmental conditions.

Ruiz-Carrasco et al. (2011) observed an elevated proline concentration in 15-day-old seedlings of four Chilean quinoa genotypes at 300 mM NaCl stress. The genotypes could be grouped into a twofold rise and those with three- to fivefold more proline than under non-saline conditions. However, it has been observed that contribution of glycine betaine and total proline to cell osmotic adjustment, accumulated in plants of quinoa exposed to salinity, is negligible due to far too low concentrations (Hariadi et al. 2011). It might be due to their osmoprotective function on cellular and subcellular organelles. Also, physiologically related concentrations of free amino acids as well as glycine betain (Cuin and Shabala 2005, 2007) regulate K^+ movement across the cell plasma membrane adjusting cell Ψ_w by indirectly regulating the concentration of this ion. Pottosin et al. (2014) observed that a precursor of glycine betain (choline) clogs SV pathways in leaf and root cell vacuoles, playing a major role in Na^+ sequestration, to prevent Na^+ flux out of the cell vacuole. Even under apoplastic low Ψ_w in salinity, a plant adjusts cell turgidity maintaining growth.

5.3.2.6 Antioxidants

Both osmotic stress and Na^+ toxicity lead to overproduction of reactive oxygen species (ROS) causing lethal effects on proteins, DNA, membranes, and pigments (Munns and Tester 2008; Bose et al. 2014). Antioxidants detoxify ROS, thus enabling plants to adapt to abiotic stress.

The defense against ROS is activated in the presence of organic osmolytes which not only play a role in osmotic adjustment but also act as antioxidants (Szabados and Savoure 2010). Some of these organic molecules may directly act as ROS scavengers, while some act as osmoprotectants or molecular chaperons shielding PSII from oxidative stress (Shabala et al. 2012). To validate this hypothesis, foliar-applied glycine betaine was found to mitigate adverse influence of oxidative stress induced by UV light affecting photosynthesis in quinoa (Shabala et al. 2012).

Polyamines (PAs), i.e., spermine (Spm), spermidine (Spd), and putrescine (Put), are aliphatic polycations acting as plant growth regulators especially in higher plants also playing a role in stress responses in crop plants (Alcazar et al. 2010). There are many reports proving that these PAs play an osmoprotective and antioxidative role during stress conditions (Tang and Newton 2005; Hussain et al. 2011). Kusano et al. (2008) observed the role of PAs in regulating ionic channels and transporters. PAs have protective functions, i.e., on photosynthetic apparatus as well as on membranes, from Spm and Spd for mitigating drought and salt stress (Yamaguchi et al. 2007; Duan et al. 2008).

Ruiz-Carrasco et al. (2011) compared four Chilean quinoa accessions under salinity levels of 150 and 300 mM NaCl. It was noticed that (Spd/Spm)/Put ratio in BO78 accession was significantly lower as compared to other accessions, thus indicating this accession to be sensitive to salt. On the other hand, a high proline accumulation was a salt-tolerant trait of this accession.

The antioxidant system is composed of enzymes (e.g., superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT)) and nonenzymes, i.e., vitamins and phenolic compounds. Amjad et al. (2015) revealed enhanced activity of some antioxidant enzymes in leaves of quinoa cv. Titicaca when exposed to 300 mM NaCl ionic as well as nonionic (600 mM mannitol) salt stress. Together nonionic and ionic salt stress caused improved activities of enzyme antioxidants SOD, POD, and CAT in leaf tissues up to 2.33-, 5.5-, and 3.98-fold, respectively. Ismail et al. (2016) explored both enzymatic and nonenzymatic antioxidant profiles in leaves of two contrasting quinoa genotypes related to salt tolerance. The clear trend of enhanced activity was only found for the enzymatic antioxidant, superoxide dismutase (SOD), under salinity (400 mM NaCl) with almost double production in the Salar region cultivar Utusaya compared to Danish cultivar Titicaca. Total antioxidant capacity (TAC) was age-dependent in leaves, where young leaves displayed higher (1.5-fold) TAC than older ones, and Utusaya also showed higher TAC. While considering the nonenzymatic component of the antioxidant system, a profiling of phenolic compounds in salt-stressed leaves of both cultivars demonstrated that rutin was the main phenolic compound which accumulated 27.5 times more in young leaves of both cultivars (Ismail et al. 2016). It is confirmed in quinoa that both enzymatic and nonenzymatic components of the antioxidant system operate to detoxify ROS.

5.4 Genetic Studies

5.4.1 Na^+ Transporters in Quinoa

In quinoa the capability for translocation and ion uptake during saline regimes has been explored by leaf sap K^+, Na^+ along with other ionic measurements and by monitoring the activities of transporters responsible for ionic movements. Through studies of molecular techniques, genes related to Na^+ exclusion have been cloned in many plant species to identify the level of salt tolerance (Shi et al. 2003). A gene

Table 5.2 Upregulated genes and their functions during salinity

Genes	Function	References
CqSOS1A	Na^+ exclusion in leaves	Maughan et al. (2009)
CqSOS1B	Na^+ exclusion in leaves	Ruiz-Carrasco et al. (2011)
CqSOS1	Na^+ exclusion in roots	Ruiz-Carrasco et al. (2011)
CqNHX1	Na^+ dumping in root/shoot vacuole	Morales et al. (2011)

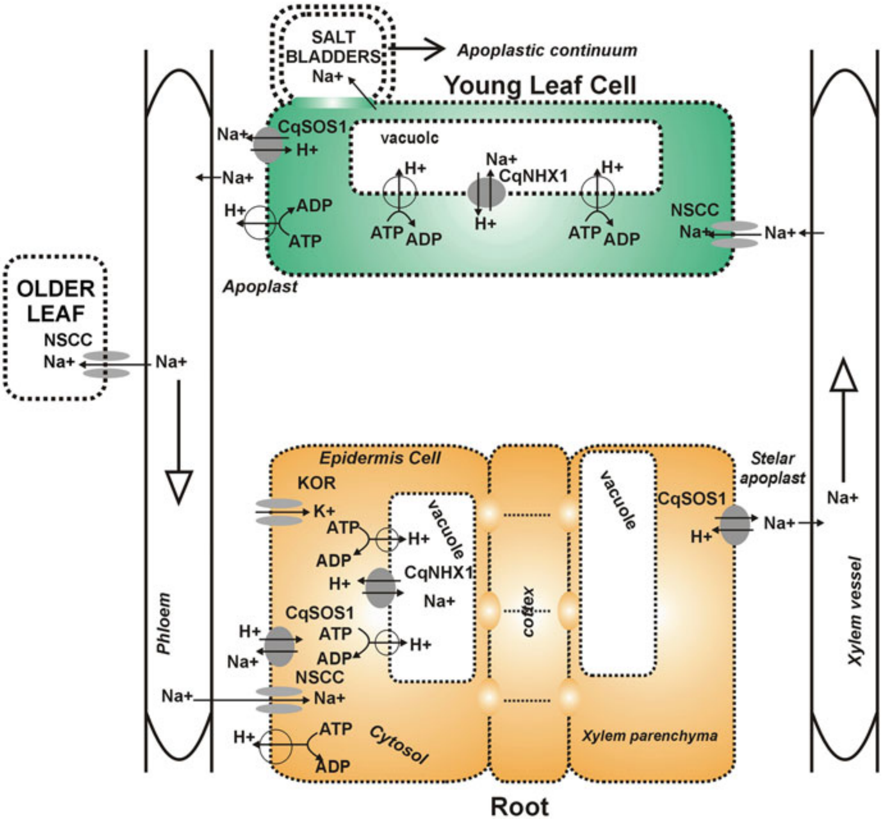

Fig. 5.2 Summary diagram of Na^+ transport in quinoa plant

NHX1 of *Arabidopsis thaliana* encodes tonoplast restricted Na^+/H^+ antiporter which is thought to be involved in Na^+ locking in the vacuole, a critical process known as compartmentation to avoid Na^+ toxicity in cytosol. This ion also works as additional osmoticum in cytosol for turgor maintenance and uptake of water (Flowers and Colmer 2008). The genes responsible for Na^+ exclusion and compartmentation are summarized in Table 5.2 and Fig. 5.2.

5.5 Nutritional Profile

Quinoa seeds are gluten-free and a remarkable source of food for a complete nutrition, owing to their superior protein contents, comprised of all essential amino acids, having high mineral contents such as Mg, Fe, Zn, and Ca and bioactive compounds. Excess salinity alters composition of cereals (Ashraf 2014) and quinoa (Aloisi et al. 2016), thus affecting functional properties. Studies of nutritional quality of quinoa seeds harvested from saline soils will give strategic information for its promotion in new regions and also will be helpful in identification of nutritionally superior genotypes.

Titicaca, a cultivar bred in Denmark (Jacobsen 2017; Hariadi et al. 2011) and cultivar Hualhuas of Peru (Koyro and Eisa 2008), could produce seed even at salt stress of 500 mM NaCl. Seed yields along with C/N ratio were found lower in seeds harvested from 300 mM salinity as compared to non-saline conditions. The lowered C/N ratio was found linked with higher protein content of seeds. When quinoa seeds were harvested from three locations of the Mediterranean region irrigated with saline water of 2.3, 16.3, and 18.9 dS m^{-1}, respectively, it was revealed that saline irrigation caused differences in mineral content.

Protein, lipid, fiber, and carbohydrate were determined in a saline-irrigated field in Southern Italy, showing similar values in seeds harvested from normal irrigated fields. Only fiber content was higher under saline regimes possibly due to different comparative amounts of hull versus rest of seed (Pulvento et al. 2012). Wu et al. (2016) recorded more protein in seeds of quinoa obtained from plants grown at 32 dS m^{-1} Na2SO4 as compared to non-saline control plants.

Seeds of ten quinoa accessions (nine from the highland of Bolivia and one from Argentina) were grown under two drought prone locations with different values of soil EC (2 and 7 in Encalilla and Patacamaya, respectively). Seed protein percentage was variable mainly due to genotypes but also affected by environment and their interactions. Differences were recorded in the amino acid profile (Gonzalez et al. 2011). Karyotis et al. (2003) evaluated seeds harvested from plants grown in Central Greece under normal (L1) and saline-sodic (L2) soil conditions. Quinoa accessions of different origins (Denmark, Brazil, Chile, the Netherlands, and the United Kingdom) showed a stable protein concentration among accessions at L2 but different at L1. Protein content was higher at L2 than L1, with a negative correlation between seed protein content and seed yield. Several minerals (Ca, Mg, K, Mn, and Zn) were found significantly lower at saline-sodic conditions indicating restricted ion accumulation. Accessions from South America were superior in terms of mineral accumulations in seed under both normal and saline-sodic regimes.

Aloisi et al. (2016) used three Chilean ecotypes to examine alterations in total phenol (TPC), flavonoid (TFC), total antioxidant activity (AA), and profile of amino acids in protein extract of quinoa seeds harvested from plants exposed to two salt levels (100 and 300 mM NaCl). Chilean landraces under study were a salares ecotype (R49) and two coastal/lowland ecotypes (Villarrica (VR) and VI-1). All amino acids except Met and Ala in R49 were reduced in seeds from salt-affected plants, particularly in ecotype VI-1, while free amino acids remained stable or even increased in R49 by salinity as compared to VI-1 and VR, indicating greater salt tolerance in the ecotype from salares. Furthermore, VR showed highest AA as well as TPC under non-saline conditions. Enhanced TPC was observed in all ecotypes tested showing maximum value in R49, and increased radical scavenging capabilities were recorded in VR and R49.

Phenolic and vitamin antioxidants reduce lipid peroxidation and contribute to the nutraceutical and nutritional profile of quinoa. Gómez-Caravaca et al. (2012) evaluated the influence of saline irrigation on phenolic contents in seeds of Titicaca. Small changes were observed in the level of these bioactive molecules both due to limited irrigation without or with salt addition, while in another study it was reported that saline irrigation causes decrease in the free phenolic compounds (Gómez-Caravaca et al. 2012). Considering another vital class of antioxidant compounds, initial results depict that the modulations occurred in tocopherol (vitamin E) content of leaves and seeds of four Chilean accessions raised on saline (300 mM NaCl) regime showing increasing trend depending on genotype.

Another interesting feature of quinoa seed is that its pericarp contains up to 5% saponin with a broad spectrum of properties (antifungal, antimicrobial, insecticidal, etc.) and with industrial value as surfactants and detergents (Ruiz et al. 2017). It adds a bitter taste which is negative for human consumption. On the other hand, saponin production may be regarded as an asset in quinoa as a renewable and alternative source of this compound (Woldemichael and Wink 2001; Carlson et al. 2012; Ruiz et al. 2017). 30% higher saponin content has been reported under salinity as compared to non-saline regimes (Gómez-Caravaca et al. 2012). After 2 years' experimentation under field conditions using cv. Titicaca, Pulvento et al. (2012) documented a linear rise in seed saponin content under increased salinity, while in another study Gómez-Caravaca et al. (2012) showed a 50% decrease in saponin content with increased salinity. These contrasting results need more studies in order to observe effect of salinity on grain saponin contents.

Salt stress may regulate the synthesis of bioactive compounds, thus influencing quinoa's nutritional profile. Therefore, growing quinoa on salt-affected soil could be a sustainable practice, to diminish saponin in the seed testa of quinoa. In addition, this influence can be utilized as a good tactic to avoid removal of seed outer layers where minerals and vitamins are localized (Konishi et al. 2004). These two opposite findings suggest further studies to explore the mechanistic bases linking salt stress with saponin biosynthesis. A new study demonstrated genome sequencing of quinoa which facilitated the identification of the transcription factor likely to control the triterpenoid saponin synthesis in seeds (Jarvis et al. 2017). The finding is expected to ease future research on selection for sweet varieties of quinoa. In general, the high genetic variability in quinoa represents a precious resource, which can be exploited for selecting and breeding cultivars adapted to the most diverse soil and climatic conditions (Zurita-Silva et al. 2014).

Overall, the nutritional profile was not significantly affected by salinity but was even improved in some cases (Table 5.3).

Table 5.3 Nutritional properties of quinoa and various cereals, influenced by salinity

Crop	% Dry weight			%				ppm				
	Protein[a]	Fat[a]	Fibre[a]	Ca[b]	P[b]	Mg[b]	K[b]	Na[b]	Fe[b]	Cu[a]	Mn[b]	Zn[b]
Quinoa	17	5.0	7	0.19	0.47	0.26	0.87	115	205	67	128	50
Barley	14.7	1.1	2.0	0.08	0.42	0.12	0.56	200	50	8	16	15
Corn	8.7	3.9	1.7	0.7	0.36	0.14	0.39	900	21	–	–	–
Wheat	12.0	1.6	2.7	0.05	0.36	0.16	0.52	900	50	7	–	14

Source: FAO (2017)
[a]Quinoa remains stable or improved under salinity (Karyotis et al. 2003; Wu et al. 2016)
[b]Minerals (Ca, P, Mg, K, Fe, Mn) which were found less in seeds of some quinoa harvested from saline-sodic fields (Karyotis et al. 2003)

5.6 Conclusion

Quinoa is a halophyte which can grow on salt-affected soils as demonstrated in both greenhouse and field trials under moderate to high salt regimes (10–750 mM NaCl). The information gathered and summarized here shows that the wide genetic diversity for salt tolerance is linked to multiple stress tolerance mechanisms expressed under different agroecological conditions, such as cold, drought, and salinity. Some quinoa accessions are more salt tolerant than others, but quinoa in general tolerates higher salinity levels compared to any other crop species. The genetic diversity, however, seems to be a precious source for selection and breeding for adverse climate and soil conditions. Information about the morphological, physiological, and molecular basis of salt tolerance can assist breeders in selection based on traits of interest. Nutritional properties are affected by salinity. Due to its stress tolerance and nutritional benefits, the worldwide demand of quinoa has increased. Quinoa could improve livelihood and food security for farmers in salt- and drought-affected areas.

References

Adolf VI, Shabala S, Andersen MN, Razzaghi F, Jacobsen S-E (2012) Varietal differences of quinoa's tolerance to saline conditions. Plant Soil 357:117–129

Adolf VI, Jacobsen S-E, Shabala S (2013) Salt tolerance mechanisms in quinoa *Chenopodium Quinoa's Willd*. Environ Exp Bot 92:43–54

Agarie S, Shimoda T, Shimizu Y, Baumann K, Sunagawa H, Kondo A, Ueno O, Nakahara T, Nose A, Cushman JC (2007) Salt tolerance, salt accumulation, and ionic homeostasis in an epidermal bladder-cell-less mutant of the common ice plant *Mesembryanthemum crystallinum*. J Exp Bot 58:1957–1967

Aguilar PC, Cutipa Z, Machaca E, López M, Jacobsen S-E (2003) Variation of proline content of quinoa (*Chenopodium quinoa* Willd.) in high beds (Waru Waru). Food Rev Int 19:121–127

Aloisi I, Parrotta L, Ruiz KB, Landi C, Bini L, Cai G, Biondi S, Duca SD (2016) New insight into quinoa seed quality under salinity: Changes in proteomic and amino acid profiles, phenolic content, and antioxidant activity of protein extracts. Front Plant Sci 7:1–21

Amjad M, Akhtar SS, Yang A, Akhtar J, Jacobsen S-E (2015) Antioxidative response of quinoa exposed to iso-osmotic, ionic and non-ionic salt stress. J Agron Crop Sci 201:452–460

Ashraf M (2014) Stress-induced changes in wheat grain composition and quality. Crit Rev Food Sci Nutr 54(12):1576–1583

Barrett-Lennard EG (2002) Restoration of saline land through revegetation. Agric Water Manag 53:213–226

Bazile D, Jacobsen S-E, Verniau A (2016) The global expansion of Quinoa: trends and limits. Front Plant Sci 7:622. https://doi.org/10.3389/fpls.2016.00622

Becker VI, Goessling JW, Duarte B, Cacador I, Liu F, Rosenqvist E, Jacobsen S-E (2017) Combined effects of soil salinity and high temperature on photosynthesis and growth of quinoa plants (*Chenopodium quinoa*). Funct Plant Biol 44:665–678

Blumwald E, Aharon GS, Apse MP (2000) Sodium transport in plant cells. Biochim Biophys Acta 1465:140–151

Bonales-Alatorre E, Pottosin I, Shabala L, Chen ZH, Zeng F, Jacobsen S-E, Shabala S (2013) Differential activity of plasma and vacuolar membrane transporters contributes to genotypic differences in salinity tolerance in a halophyte species, *Chenopodium quinoa*. Int J Mol Sci 14:9267–9285

Bose J, Rodrigo-Moreno A, Shabala S (2014) ROS homeostasis in halophytes in the context of salinity stress tolerance. J Exp Bot 65:1241–1257

Burrieza HP, Koyro HW, Tosar LM, Kobayashi K, Maldonado S (2012) High salinity induces dehydrin accumulation in Chenopodium quinoa Willd. cv. Hualhuas embryos. Plant Soil 354 (1–2):69–79

Carjuzaa P, Castellión M, Distéfano AJ, del Vas M, Maldonado S (2008) Detection and subcellular localization of dehydrin-like proteins in quinoa (*Chenopodium quinoa* Willd.) embryos. Protoplasma 233:149–156

Carlson D, Fernández JA, Poulsen HD, Nielsen B, Jacobsen SE (2012) Effects of quinoa hull meal on piglet performance and intestinal epithelial physiology. J Anim Physiol Anim Nutr 96 (2):198–205

Cuin TA, Shabala S (2005) Exogenously supplied compatible solutes rapidly ameliorate NaCl-induced potassium efflux from barley roots. Plant Cell Physiol 46:1924–1933

Cuin TA, Shabala S (2007) Compatible solutes reduce ROS induced potassium efflux in Arabidopsis roots. Plant Cell Environ 30:875–885

Debez A, Hamed KB, Grignon C, Abdelly C (2004) Salinity effects on germination, growth, and seed production of the halophyte *Cakile maritima*. Plant Soil 262:179–189

Demidchik V, Cuin TA, Svistunenko D, Smith SJ, Miller AJ, Shabala S, Sokolik A, Yurin V (2010) Arabidopsis root K+ efflux conductance activated by hydroxyl radicals: Single-channel properties, genetic basis and involvement in stress-induced cell death. J Cell Sci 123:1468–1479

Dini I, Tenore GD, Dini A (2005) Nutritional and anti-nutritional composition of Kancolla seeds: an interesting and underexploited Andine food plant. Food Chem 92:125–132

Duan J, Li J, Guo S, Kang Y (2008) Exogenous spermidine affects polyamine metabolism in salinity-stressed *Cucumis sativus* roots and enhances short-term salinity tolerance. J Plant Physiol 165:1620–1635

FAO Statistical Year Book (2012) World Food and Agriculture. Food and Agriculture Organization of the United Nation, Rome, p 366

FAO (2017) International Year of Quinoa 2013, What is quinoa?, Nutritional value accessed on: June 13, 2017. Available online at: http://www.fao.org/quinoa2013/what-is-quinoa/nutritional-value/en/

Flowers TJ, Colmer TD (2008) Salinity tolerance in halophytes. New Phytol:945–963

Ghassemi F, Jakeman AJ, Nix HA (1995) Salinisation of land and water resources: human causes, management and case studies. University of New South Wales Press, Sydney, Australia

Gómez-Pando LR, Álvarez-Castro R, Eguiluz-De La Barra A (2010) Effect of salt stress on Peruvian germplasm of Chenopodium quinoa Willd.: a promising crop. J Agron Crop Sci 196 (5):391–396

Gómez-Caravaca AM, Iafelice G, Lavini A, Pulvento C, Caboni MF, Marconi E (2012) Phenolic compounds and saponins in quinoa samples (Chenopodium quinoa Willd.) grown under different saline and nonsaline irrigation regimens. J Agric Food Chem 60(18):4620–4627

Gonzalez JA, Konishi Y, Bruno M, Valoy M, Prado FE (2011) Interrelationships among seed yield, total protein and amino acid composition of ten quinoa (*Chenopodium quinoa*) cultivars from two different agroecological regions. J Sci Food Agric 92:1222–1229

Hariadi Y, Marandon K, Tian Y, Jacobsen S-E, Shabala S (2011) Ionic and osmotic relations in quinoa (*Chenopodium quinoa* Willd.) plants grown at various salinity levels. J Exp Bot 62:185–193

Hasegawa PM, Bressan RA, Zhu JK, Bohnert HJ (2000) Plant cellular and molecular responses to high salinity. Annu Rev Plant Physiol Plant Mol Biol 51:463–499

Hirich A, Jelloul A, Choukr-Allah R, Jacobsen S-E (2014) Saline water irrigation of quinoa and chickpea: seedling rate, stomatal conductance and yield responses. J Agron Crop Sci 200:378–389

Hossain, MA (2010) Global warming induced sea level rise on soil, land and crop production loss in Bangladesh. 19th World congress of soil science, soil solutions for a changing World, Brisbane

Hussain SS, Ali M, Ahmad M, Siddique KHM (2011) Polyamines: natural and engineered abiotic and biotic stress tolerance in plants. Biotechnol Adv 29:300–311

Inan G, Zhang Q, Li PH, Wang Z, Cao Z, Zhang H, Zhang C, Quist TM, Goodwin SM, Zhu J, Shi H, Damsz B, Charbaji T, Gong Q, Ma S, Fredricksen M, Galbraith DW, Jenks MA, Rhodes D, Hasegawa PM, Bohnert HJ, Joly RJ, Bressan RA, Zhu JK (2004) Salt cress. A halophyte and cryophyte Arabidopsis relative model system and its applicability to molecular genetic analyses of growth and development of extremophiles. Plant Physiol 135:1718–1737

Iqbal S, Maqsood Ahmed Basra S, Afzal I, Wahid A (2017) Exploring potential of well adapted Quinoa lines for salt tolerance. Int J Agric Biol 19(4)

Iqbal S, Basra SM, Afzal I, Wahid A, Saddiq MS, Hafeez MB, Jacobsen SE (2019) Yield potential and salt tolerance of quinoa on salt-degraded soils of Pakistan. J Agron Crop Sci 205(1):13–21

Ismail H, Maksimovic JD, Maksimovic V, Shabala L, Živanovic BD, Tian Y, Jacobsen S-E, Shabala S (2016) Rutin, a flavonoid with antioxidant activity, improves plant salinity tolerance by regulating K^+ retention and Na^+ exclusion from leaf mesophyll in quinoa and broad beans. Funct Plant Biol 43:75–86

Iyengar ERR, Reddy MP (1997) Photosynthesis in highly salt tolerant plants. In: Pesserakli M (ed) Handbook of plant and crop stress. Marcel Dekker, New York, Basel, Hong Kong, pp 897–909

Jacobsen S-E (2017) Adaptation and scope for quinoa in Northern latitudes of Europe. J Agro Crop Sci 203:603–613. https://doi.org/10.1111/jac.12228

Jacobsen S-E, Mujica A, Ortiz R (2003) The global potential for quinoa and other Andean crops. Food Rev Int 19:139–148

Jarvis DE, Ho YS, Lightfoot DJ, Schmöckel SM, Li B, Borm TJA, Ohyanagi H, Mineta K, Michell CT, Saber N, Kharbatia NM, Rupper RR, Sharp AR, Dally N, Boughton BA, Woo YH, Gao G, EGWM S, Guo X, Momin AA, Negrão S, Al-Babili S, Gehring C, Roessner U, Jung C, Murphy K, Arold ST, Gojobori T, CGV L, ENV L, Jellen EN, Maughan PJ, Tester M (2017) The genome of *Chenopodium quinoa*. Nature 542:307–312

Jou Y, Wang YL, Yen HE (2007) Vacuolar acidity, protein profile, and crystal composition of epidermal bladder cells of the halophyte *Mesembryanthemum crystallinum*. Funct Plant Biol 34:353–359

Karyotis T, Iliadis C, Noulas C, Mitsibonas T (2003) Preliminary research on seed production and nutrient content for certain quinoa varieties in a saline-sodic soil. J Agron Crop Sci 189:402–408

Konishi Y, Hirano S, Tsuboi H, Wada M (2004) Distribution of minerals in quinoa (Chenopodium quinoa willd.) seeds. Biosci Biotechnol Biochem 68:231–234

Koyro HW, Eisa SS (2008) Effect of salinity on composition, viability and germination of seeds of Chenopodium quinoa Willd. Plant Soil 302(1–2):79–90

Kusano T, Berberich T, Tateda C, Takahashi Y (2008) Polyamines: essential factors for growth and survival. Planta 228:367–381

Maas EV, Grattan SR (1999) Crop yields as affected by salinity. Agric drainage 38:55–108

Maas EV, Hoffmann GJ (1977) Crop salt tolerance—current assessment. In: Proceedings of the American Society of Civil Engineers. J Irrig Drain Div 103:115–134

Malcolm CV, Lindley VA, O'Leary JW, Runciman HV, Barrett-Lennard EG (2003) Halophyte and glycophyte salt tolerance at germination and the establishment of halophyte shrubs in saline environments. Plant Soil 253:171–185

Maughan PJ, Turner TB, Coleman CE, Elzinga DB, Jellen EN, Morales JA, Udall JA, Fairbanks DG, Bonifacio A (2009) Characterization of salt overly sensitive 1 (SOS1) gene homoeologs in quinoa (*Chenopodium quinoa* willd.). Genome 52:647–657

Morales AJ, Bajgain P, Garver Z, Maughan PJ, Udall JA (2011) Physiological responses of *Chenopodium quinoa* to salt stress. Int J Plant Physiol Biochem 3:219–232

Munns R (2005) Genes and salt tolerance: bringing them together. New Phytol 167:645–663

Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59:651–681

Munns R, James RA, Läuchli A (2006) Approaches to increasing the salt tolerance of wheat and other cereals. J Exp Bot 57(5):1025–1043

Orsini F, Accorsi M, Gianquinto G, Dinelli G, Antognoni F, Carrasco KBR, Martinez EA, Alnayef M, Marotti I, Bosi S (2011) Beyond the ionic and osmotic response to salinity in *Chenopodium quinoa*: functional elements of successful halophytism. Funct Plant Biol 38:818–831

Panta S, Flowers T, Lane P, Doyle R, Haros G, Shabala S (2014) Halophyte agriculture: success stories. Environ Exp Bot 107:71–83

Peterson A, Murphy K (2015) Tolerance of lowland quinoa cultivars to sodium chloride and sodium sulfate salinity. Crop Sci 55(1):331–338

Pottosin I, Bonales-Alatorre E, Shabala S (2014) Choline but not its derivative betaine blocks slow vacuolar channels in the halophyte Chenopodium quinoa: Implications for salinity stress responses. FEBS Lett 588(21):3918–3923

Prado FE, Boero C, Gallardo M, Gonzalez JA (2000) Effect of NaCl on germination, growth, and soluble sugar content in *Chenopodium quinoa* Willd. seeds. Bot Bull Acad Sinica 41:27–34

Pulvento C, Riccardi M, Lavini A, d'Andria R, Iafelice G, Marconi E (2010) Field trial evaluation of two chenopodium quinoa genotypes grown under rain-fed conditions in a typical Mediterranean environment in South Italy. J Agron Crop Sci 196(6):407–411

Pulvento C, Riccardi M, Lavini A, Iafelice G, Marconi E, d'Andria R (2012) Yield and quality characteristics of quinoa grown in open field under different saline and non-saline irrigation regimes. J Agron Crop Sci 198(4):254–263

Qadir M, Oster J, Schubert S, Noble A, Sahrawat K (2007) Phytoremediation of sodic and saline-sodic soils. Adv Agron 96:197–247

Qiu QS, Guo Y, Dietrich MA, Schumaker KS, Zhu JK (2002) Regulation of SOS1, a plasma membrane Na^+/H^+ exchanger in *Arabidopsis thaliana*, by SOS2 and SOS3. Proc Natl Acad Sci 99:8436–8441

Razzaghi F, Ahmadi SH, Adolf VI, Jensen CR, Jacobsen S-E Andersen MN (2011a) Water relations and transpiration of quinoa (*Chenopodium quinoa* Willd.) under salinity and soil drying. J Agron Crop Sci 197:348–360

Razzaghi F, Ahmadi SH, Jensen CR, Jacobsen S-E, Andersen MN (2011b) The salt tolerance of quinoa measured under field conditions. In: International Congress on Irrigation and Drainage, Teheran, Iran, 15–23 October 2011, pp. 149–153.

Razzaghi F, Jacobsen S-E, Jensen CR, Andersen MN (2015) Ionic and photosynthetic homeostasis in quinoa challenged by salinity and drought–mechanisms of tolerance. Funct Plant Biol 42:136–148

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

Riccardi M, Pulvento C, Lavini A, d'Andria R, Jacobsen S-E (2014) Growth and ionic content of quinoa under saline irrigation. J Agron Crop Sci 200:246–260

Ruffino AMC, Rosa M, Hilal M, González JA, Prado FE (2010) The role of cotyledon metabolism in the establishment of quinoa (*Chenopodium quinoa*) seedlings growing under salinity. Plant Soil 326:213–224

Ruiz KB, Biondi S, Martínez EA, Orsini F, Antognoni F, Jacobsen S-E (2016) Quinoa—a model crop for understanding salt tolerance mechanisms in halophytes. Plant Biosystems 150:357–371. https://doi.org/10.1080/11263504.2015.1027317

Ruiz KB, Khakimov B, Engelsen SB, Bak S, Biondi S, Jacobsen S-E (2017) Quinoa seed coats as an expanding and sustainable source of bioactive compounds: An investigation of genotypic diversity in saponin profiles. Industrial Crop Prod 104:156–163. https://doi.org/10.1016/j.indcrop.2017.04.007

Ruiz-Carrasco K, Antognoni F, Coulibaly AK, Lizardi S, Covarrubias A, Martínez EA, Molina-Montenegro MA, Biondi S, Zurita-Silva A (2011) Variation in salinity tolerance of four lowland genotypes of quinoa (*Chenopodium quinoa* Willd.) as assessed by growth, physiological traits, and sodium transporter gene expression. Plant Physiol Biochem 49:1333–1341

Shabala S, Mackay A (2011) Ion transport in halophytes. Adv Bot Res 57:151–187

Shabala L, Mackay A, Tian Y, Jacobsen S-E, Zhou D, Shabala S (2012) Oxidative stress protection and stomatal patterning as components of salinity tolerance mechanism in quinoa (Chenopodium quinoa Willd). Physiologia Plantarum 146:26–38

Shabala S, Hariadi Y, Jacobsen S-E (2013) Genotypic difference in salinity tolerance in quinoa is determined by differential control of xylem Na^+ loading and stomatal density. J Plant Physiol 170:906–914

Shi H, Lee BH, Wu SJ, Zhu JK (2003) Overexpression of a plasma membrane Na+/H+ antiporter gene improves salt tolerance in Arabidopsis thaliana. Nat Biotechnol 21(1):81–85

Suhayda CG, Redmann RE, Harvey BL, Cipywnyk AL (1992) Comparative response of cultivated and wild barley species to salinity stress and calcium supply. Crop Sci 32:154–163

Sun Y, Lindberg S, Morgan S, Shabala S, Jacobsen S-E (2017) A comparative analysis of cytosolic Na^+ changes under salinity between halophyte quinoa (*Chenopodium quinoa*) and glycophyte pea (*Pisum sativum*). Env Exp Bot 141:154–160. https://doi.org/10.1016/j.envexpbot.2017.07.003

Szabados L, Savoure A (2010) Proline: a multifunctional amino acid. Trends Plant Sci 15:89–97

Tang W, Newton RJ (2005) Polyamines reduce salt-induced oxidative damage by increasing the activities of antioxidant enzymes and decreasing lipid peroxidation in Virginia pine. Plant Growth Regul 46:31–43

Tobe K, Li X, Omasa K (2000) Seed germination and radicle growth of a halophyte, *Kalidium caspicum* (Chenopodiaceae). Ann Bot 85:391–396

Vashev B, Gaiser T, Ghawana T, de Vries A, Stahr K (2010) Biosafor Project Deliverable 9: Cropping Potentials for Saline Areas in India, Pakistan and Bangladesh. University of Hohenheim, Hohenheim

Wicke B, Smeets E, Dornburg V, Vashev B, Gaiser T, Turkenburg W, Faaij A (2011) The global technical and economic potential of bioenergy from salt-affected soils. Energ Environ Sci 4:2669–2681

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

Woldemichael GM, Wink M (2001) Identification and biological activities of triterpenoid saponins from *Chenopodium quinoa*. J Agric Food Chem 49:2327–2332

Wu G, Peterson AJ, Morris CF, Murphy KM (2016) Quinoa seed quality response to sodium chloride and sodium sulfate salinity. Front Plant Sci 7:790

Yamaguchi K, Takahashi Y, Berberich T, Imai A, Takahashi T, Michael AJ, Kusano T (2007) A protective role for the polyamine spermine against drought stress in Arabidopsis. Biochem Biophys Res Commun 352:486–490

Yang A, Akhtar SS, Iqbal S, Amjad M, Naveed M, Zahir ZA, Jacobsen S-E (2016) Enhancing salt tolerance in quinoa by halotolerant bacterial inoculation. Funct Plant Biol 43:632–642

Yazar A, Incekaya Ç, Sezen SM, Jacobsen SE (2015) Saline water irrigation of quinoa (Chenopodium quinoa) under Mediterranean conditions. Crop Pasture Sci 66(10):993–1002

Zurita-Silva A, Fuentes F, Zamora P, Jacobsen S-E, Schwember A (2014) Breeding quinoa (*Chenopodium quinoa* Willd.): potential and perspectives. Mol Breed 34:13–30

Chapter 6
Cultivation of Quinoa (*Chenopodium quinoa*) in Desert Ecoregion

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Abstract Field experiments with the Andean grain crop, quinoa (keen-waa) were tested in three localities of United Arab Emirates at two, three and five sowing densities in 2016–2017. Four quinoa genotypes were utilized (two selected quinoa lines: ICBA-Q3 and ICBA-Q5; and two introduced quinoa genotypes: Titicaca and Amarilla Sacaca). Sowing density did not affect aerial and ground dry biomass. However, grain yield and harvest index were different among quinoa genotypes. Quantity of irrigation had effect on the production of biomass as in Dubai and Al Dhaid, though water with low salinity was used. Photoperiod and temperature were appropriate for the growth and development of quinoa genotypes in the three localities. Quinoa genotypes can grow in sandy native soils. The period used for cultivating quinoa between October to February were optimal than April. Conditions of drip irrigation should be similar, nevertheless in Abu Dhabi the conditions were at farmer level and it should be optimized.

Keywords Hot temperature · Quinoa genotypes · United Arab Emirates

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6.1 Introduction

Alternatives for food security to 2050 and the increasing population and warming temperature are to provide adequate farming systems tools, resilient crops and vegetable proteins using the agrobiodiversity (Jarvis et al. 2015; Hamdy 2016; Jacobsen 2016; Hunter et al. 2017), for developing production systems and help farmers to adapt to a range of emerging challenges (e.g. drought, water shortages, yield plateaus and changing climate, biotic and abiotic factors). Hunter et al. (2017) suggest an updated projection that production must increase around 25–70% to meet demand in 2050. In the International Quinoa Conference held in Dubai in 2016, strong interest rises on improve adaptation of quinoa as less water use crop plant in irrigation that can withstand to salinity and benefit as food and provide income for small farmers in MENA and NENA region (ICBA 2007; Dost 2016; Pulodov et al. 2016; Sepahvand et al. 2016). The Arabian Peninsula is the driest regions of the world with very low annual precipitation and hot temperatures in summer and land holds mostly sandy soils with low fertility (<0.1%) (Rao et al. 2009; Choukr-Allah et al. 2016).

Quinoa is an Andean grain-type that has strong gained popularity in the last decade in the world for its health benefits and crop adaptability to different agroecosystems (Bazile et al. 2016). The grain contains high proteins than potatoes, barley and wheat, and is gluten-free, with vitamins, minerals, and essential amino acids (Villa et al. 2014; Rodriguez et al. 2020). Peru and Bolivia produce quinoa over 95% of the worlds (Statista Report 2016). Demand speeded after the Food and Agriculture Organization (FAO) organized 2013 International Year of Quinoa (Alandia et al. 2016). There has also an increase in production from other countries which have been encouraged to start growing quinoa (Bazile et al. 2016). *Chenopodium quinoa* has a high genetic diversity, which the genotypes can be adapted to lowland, arid lands and hot temperatures as 38 °C, further in wide range of relative humidity (40–88%) and can yield with a lower precipitation of below 200 mm (Christensen et al. 2007; Glenn et al. 2013; Fita et al. 2015). Quinoa is an alternative Amaranthaceae botanical species as *Salicornia, Swaeda* and *Amaranthus spp*., and is a potentially facultative halophyte plant can perform in saline affected soils (Jacobsen et al. 2003; Gomez-Pando et al. 2010; Rao and Shahid 2013; Koyro et al. 2011). There are quinoa genotypes with late and early growth cycle (180–130 days), further to grow amid mean daily temperatures (16–22 °C) and produce a grain yield from 1.6 to 2.4 t ha^{-1} (Bertero et al. 2004).

Rao and Shahid (2012, 2013) and Chouckr-Allah et al. (2016) have preliminary demonstrated that quinoa performed well in four locations of UAE by the study of five quinoa cultivars. Sowing density is crucial to obtain an appropriate seed yield according specific seed cultivar and to control the sink relation root plant. ICBA has obtained in the last agricultural seasons promising seed yield of five quinoa lines (Rao and Shahid 2012; Choukr-Allah et al. 2016). This chapter presents result of quinoa experiments undertaken in the agricultural season 2016–2017. The aim of the trials was to evaluate the effect of sowing density on agro-morphological traits and biomass and seed yield in four genotypes of quinoa from highland, lowland and subtropical regions adapted in three localities of United Arab Emirates.

6.2 Materials and Methods

6.2.1 Locality Experiments

Locality 1: Soil in this locality basically consists in native sandy with low organic matter (<0.1%) and some shrubs and wild weeds. No organic amendments or fertilizer were applied to the plants during the experiment. Two quinoa lines (ICBA-Q3 and ICBA-Q5) bred by ICBA in Dubai after selection from USDA-AMES accession materials (Christensen et al. 2007, Choukr-Allah et al. 2016) were sown on October 18, 2016. Five sowing densities were compared according to distance between plants (cm): 2, 6, 12, 25, and 50 centimetres. Plot sizes were 3 × 2 m, and the treatments had four replications. The distance between two drip pipe lines was 50 cm. The drippers were distributed at 25 cm in the line. Phenological stages were recorded as flowering or anthesis days (FD), physiological maturity, and grain maturity in two quinoa cultivars. Harvesting of quinoa was undertaken 130 DAS.

Locality 2: Soil in Al Dhaid facility area of Agricultural Innovation Centre (AIC) of Ministry of Climate Change and Environment is a sandy texture with low organic matter (~1%). Two quinoa lines (ICBA-Q3 and ICBA-Q5) were sown on December 5, 2016. Three sowing densities were compared (12, 25 and 50 cm of space between plants). Plot sizes were 6 × 8 m, and the treatments had three replications. The distance between dripping lines was 50 cm. Harvesting of two quinoa lines was undertaken at 102 DAS.

Locality 3: This experiment was undertaken in the property of an organic agriculture farmer. Soil analysed at the laboratory of soil analysis at ICBA depicted as one of the soils with high organic content (~2%). The manager of this farm has managed the soil of the plots by crop rotations and the incorporation of animal manure (poultry and minor livestock). Three quinoa genotypes (Titicaca, Amarilla Sacaca and ICBA-Q3) were sown in the District of Al Rahba in Abu Dhabi (Table 6.1). The sowing of quinoa was carried out in a plot where previously leaf and berry vegetables were cultivated at the organic farm. The sowing was carried out on December 5, 2016, and the harvesting was undertaken at 128 DAS. Two sowing densities were compared (10 and 20 cm of space between plants). Plot sizes were 1.5 × 15 m, and the treatments had four replications. The used plant space was 10 and 20 cm, thus the number of plants per square metre were 16 and 8.

6.2.2 Irrigation and Data Collection and Analysis

The drip irrigation system installed in the three localities had two types of emitters with an estimated flow rate of water of the emitters were amid 40 and 60 $\mathrm{l\,h^{-1}\,pl^{-1}}$. This was considerably high, compared to the flow rate at ICBA, which is only 4 $\mathrm{l\,h^{-1}}$ $\mathrm{pl^{-1}}$ for each emitter. Watering was applied for only 10 min and on alternate days.

Table 6.1 Description of locality experiments

Localities	Dubai, ICBA	Al Dhaid, AIC	Abu Dhabi
Quinoa genotypes	ICBA-Q3 (AMES 13761)[a] ICBA-Q5 (NSL 106398)[a]	ICBA-Q3 ICBA-Q5	ICBA-Q5 Titicaca[b] Amarilla Sacaca[c]
Sowing density: distance between plants in cm (pl m^{-2}, values in parenthesis)	2 (100) 6 (32) 12 (16) 25 (8) 50 (4)	12 (16) 25 (8) 50 (4)	10 (16) 20 (8)
Space between lines (m)	0.5	0.5	0.6
Space between water emitter (m)	0.25	0.25	0.4
Sowing date	18.Oct.2016	5. Nov.2016	5. Dec.2016
Harvesting date	25.Feb.2017	15. Feb.2017	12. Apr2017
Days after sowing (DAS)	130	102	128
Soil texture	Sandy, very fine	Loamy sand	Sand
Water salinity (dS m^{-1})	2.8	2.08	0.7

[a]Lines developed by ICBA, Dubai after selection from USDA-AMES (Christensen et al. 2007, Choukr-Allah et al. 2016)
[b]Denmark (selected from material originated from cross between Southern Chilean and Peruvian lines) (Adolf et al. 2012, 2013)
[c]Peru (Selected material collected from Sacaca community, Pisac District) (Estrada et al. 2011)

The plots were not irrigated if there was any rainfall. The experimental plots in the three localities where organized under RCBD (randomized complete block design) with three repetitions (blocks). The plants of quinoa genotypes were harvested after completed physiological maturity (Table 6.1). Harvesting consists in number of plants contained in 1 square metre according to sowing density (number of plants). The number of plants was counted. Fresh biomass and dry biomass in shoot and root were recorded of the total number of plants of the harvested samples. Plant traits in selected sample ($n = 5$) were recorded for stem diameter (SD) and plant height (PH). The number of days to anthesis or flowering (DF), days of grain filling (maturity) and grain yield (GY) of each plot was measured in the three locality experiments. Analysis of variance (ANOVA) two ways for all the measured traits was performed using IBM SPSS Statistics 24 statistical package (IBM Corp. 2016). Tukey's test was used to carry out and compare mean differences.

6.3 Results and Discussions

6.3.1 Climate Features of Three Localities

Three localities where quinoa trials were undertaken are classified as arid according to aridity index (Table 6.2) from 0.92 to 2.20, De Martonne index climatic classification through this relation $I_{DM} < 10$ explains as an arid climate region for the three localities due to elevated temperature and low precipitation (De Martonne 1925, Croitoru et al. 2012).

During the calendar year, the temperature rises since May to July, and August holds the most scorching temperatures where open field agriculture is unable to practice (Fig. 6.1). Temperature did not vary comparing historical and within the quinoa growth period for the three localities. Average diurnal temperatures were 21.3–26.4 °C. Nevertheless, accumulated rainfall during quinoa growing season was lower in Dubai 13 mm and Al Dhaid (8.1 mm), and sole in Abu Dhabi was higher 38.9 mm.

Temperature was reliable for the four genotypes development at the three localities (Fig. 6.1). In controlled conditions Bertero et al. (1999) have demonstrated that quinoa is plant of short-day photoperiod in quinoa cultivars from highland and tropical valley from Peru. Flowering and grain filling occurred in a short-day photoperiod (10.25 h) and temperature on 21 °C. The four quinoa genotypes in the three localities had favourable photoperiod in the stages of flowering and grain filling (Fig. 6.2). Average diurnal temperature was around 21 °C as depicted in Fig. 6.1. Increasing of temperature upon the described ones can affect flowering and grain filling as Lesjak and Calderini (2017) showed with quinoa cultivars in the lowland region in Chile. Hirich and Choukr-Allah (2016) have demonstrated either in a trial under greenhouse conditions with the two quinoa lines ICBA-Q3 and ICBA-Q5 of being sensible, when environmental temperature arise over 30 °C. Chenopodium genus is sensitive to long day photoperiod as demonstrated either by Huang et al. (2001). Long photoperiod can delay phenological stages.

Table 6.2 Climatic conditions of UAE localities during quinoa growth season in 2016–2017

	DAS	I_{DM}	Tmax (°C)	Tmin (°C)	Tm (°C)	RHmax (%)	RHmin (%)	Total Precip. (mm)
Dubai	130	1.00	38.1	4.4	21.3	75	33	13
Al Dhaid	102	2.20	34.2	18	26.1	87	38	8.1
Abu Dhabi	128	0.92	41.5	11.4	26.4	89	30	38.9

Where: Days after sowing (DAS), De Martonne aridity index (I_{DM}), Maximal temperature (Tmax), minimal temperature (Tmin) and mean temperature (Tm), maximal relative humidity (RHmax), minimal relative humidity (RHmin) and total precipitation (Total precip.). Climatic for Al Dhaid and Abu Dhabi were recorded from the Airport database, and the data for Dubai was registered at the automatic climatic station of Scada

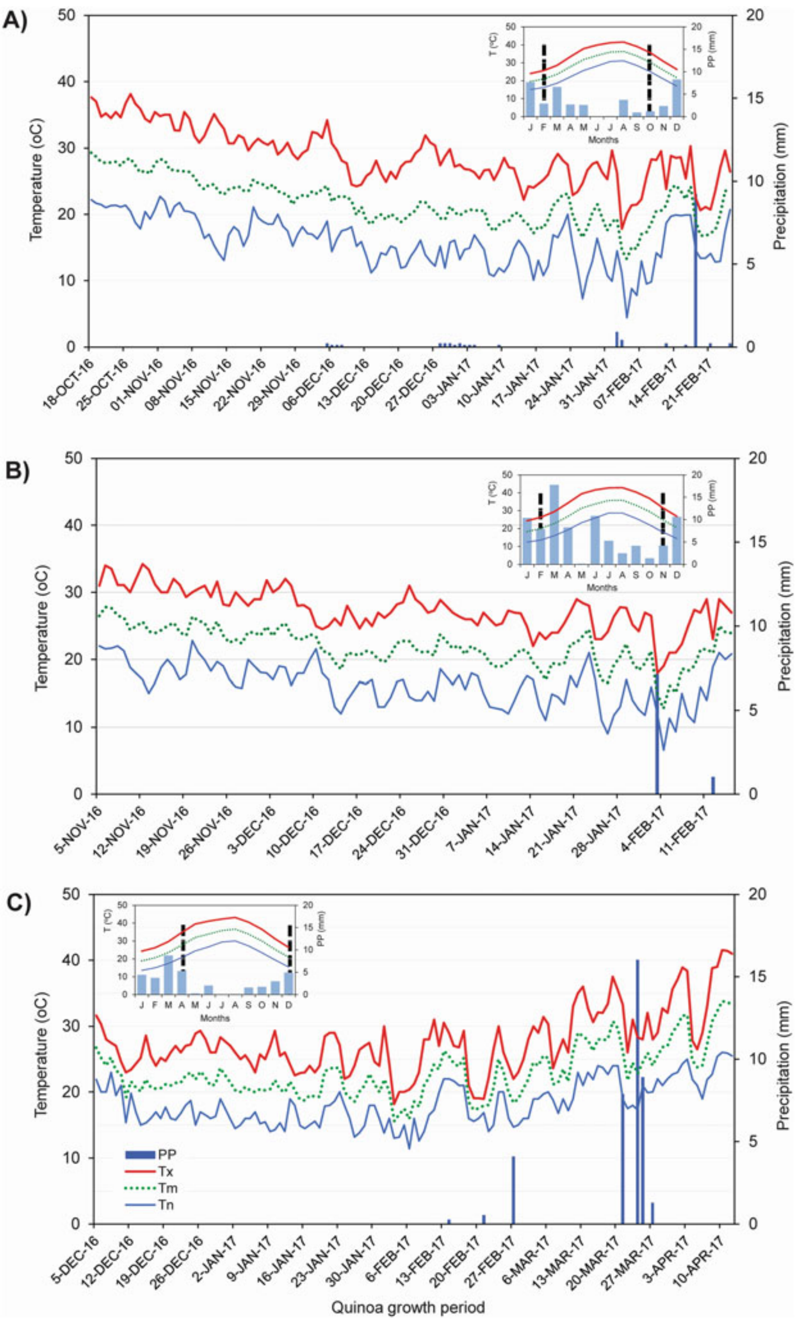

Fig. 6.1 Climatic diagram recorded during the quinoa cultivation and the ombrothermic diagram (average of 30 years shown in the small diagram) of three localities of UAE in the main diagrams: (**a**) Dubai, (**b**) Al Dhaid (Airport of Sharjah close reference) and Al Rahba (Int. Airport of Abu Dhabi). Where: maximal temperature (Tx), minimal temperature (Tn) and mean temperature

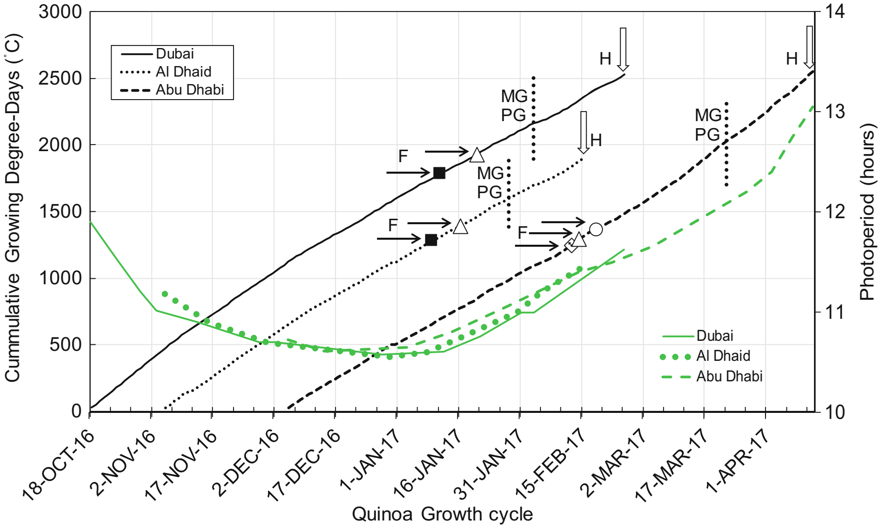

Fig. 6.2 Accumulated growing degree days (GDD) and photoperiod (hours). Phenological stages are denoted as: flowering (F), milky grain (MG), pasty grain (PG) and harvesting (H) to four genotypes in the three localities during the growth season 2016–2017. Where quinoa genotypes are denoted as: ICBA-Q3 (*Triangle*), ICBA-Q5 (*Square*), Titicaca (Circle) and Amarilla Sacaca (*Rhombus*)

6.3.2 Growing Degree Days and Photoperiod Effect on Flowering and Fructification

The agricultural season 2016–2017 for quinoa in Dubai and Abu Dhabi were warmer than in Al Dhaid (Fig. 6.1). Accumulated degree days are provided as another comparison of growing conditions. A degree day (DD) is the amount of heat that accumulates over a 24-h period when the temperature is between the lower and upper development threshold for an organism. Growing degree days (GDD) was calculated to make relation with the phenological stages of quinoa genotypes and localities (McMaster and Wilhelm 1997). In general, the lower temperature, the slower the rate of development. In quinoa, the lower development threshold is 3 °C for lowland quinoa ecotypes (Jacobsen and Bach 1998, and estimation by Bassole 2017 to quinoa genotypes for arid lands, no published), which is considered the lower temperature at which development stops.

As United Arab Emirates is in the Arabian Peninsula and classified as arid region for the hot temperatures and minimal rainfall (Fig. 6.1). Accumulated growing

Fig. 6.1 (continued) (Tm) and precipitation (PP). Vertical arrow lines in the small diagrams show start and end of quinoa growth period degree days were reported high for the growth of quinoa on Dubai and Abu Dhabi, and less for Al Dhaid. The photoperiod for the three localities had 11.9–13 h in the day from October to April. Flowering stage is important according to plant growth and fructification, and quinoa plant is sensible at long day (Bertero et al. 1999; Christiansen et al. 2010). At this stage, the quinoa lines planted in the three localities had not inconvenient at flowering stage, which ranged from 10.6 to 11 h (Fig. 6.2). Dubai and Al Dhaid had in average during flowering stage had a photoperiod of 10.45 h and 11 h in Abu Dhabi. Post-anthesis, fructification and grain development for ICBA-Q3 and Titicaca and Amarilla Sacaca had highest accumulated GDD (Fig. 6.2), but the photoperiod was not different (11 and 11.6 h). Quinoa line ICBA-Q3 had the highest accumulated GDD (1928 and 1393 °C) in Dubai and Al Dhaid. In contrast, ICBA-Q5 had 1799 °C in Dubai and lowest GDD of 1260 °C in Al Dhaid (Fig. 6.2). The quinoa genotypes used in the three localities come from lowland region and sea level (Table 6.1) and could grow and develop according to arid ecological conditions in UAE.

6.3.3 Agro-Morphological Comparison of Quinoa Genotypes in Three Localities

6.3.3.1 Grain Yield and Harvest Index

Annual crops as quinoa are highly dynamic and provide different challenges compared to other Amaranthaceae family crop species. *Chenopodium quinoa* can perform and provide varied grain and biomass yield according to location, genotype and agroecological conditions. Grain yield and harvest index (HI) were determined for four quinoa genotypes cultivated under five, three and two sowing densities (Fig. 6.3). Sowing density did not have any significant effect on grain yield of the four quinoa genotypes in the three localities (Table 6.3).

Yield of seed for the two quinoa lines in Dubai and Abu Dhabi was below 200 g m^{-2}. In Dubai at the experimental station of ICBA, seed yield of quinoa line ICBA-Q3 for five sowing densities ranged between 120 and 180 g m^{-2}. Quinoa line ICBA-Q5 ranged between 120 and 190 g m^{-2} (Fig. 6.3a). In contrast in Al Dhaid, quinoa line ICBA-Q3 had a seed yield ranged between 150 and 300 g m^{-2}. Quinoa line ICBA-Q5 had higher grain yield (Fig. 6.3b). The introduced new genotypes Amarilla Sacaca and Titicaca had lowest seed yield and either quinoa line ICBA-Q3 in Abu Dhabi (Fig. 6.3b). Rao and Shahid (2012) and Rao (2016) obtained seed yield for quinoa line ICBA-Q3 between 60.5 and 600 g m^{-2} in agricultural season 2007–2008, 2008–2009 and 2013–2014 in Al Dhaid.

Sowing density had not significant effect on harvest index in four quinoa genotypes for the three localities. Nevertheless, there were significant differences between two genotypes in Dubai, and not significant differences for genotypes in Al Dhaid and Abu Dhabi (Table 6.3). In Dubai, the two quinoa genotypes had a long growth cycle that the other two localities. In United Arab Emirates, genotypes rather

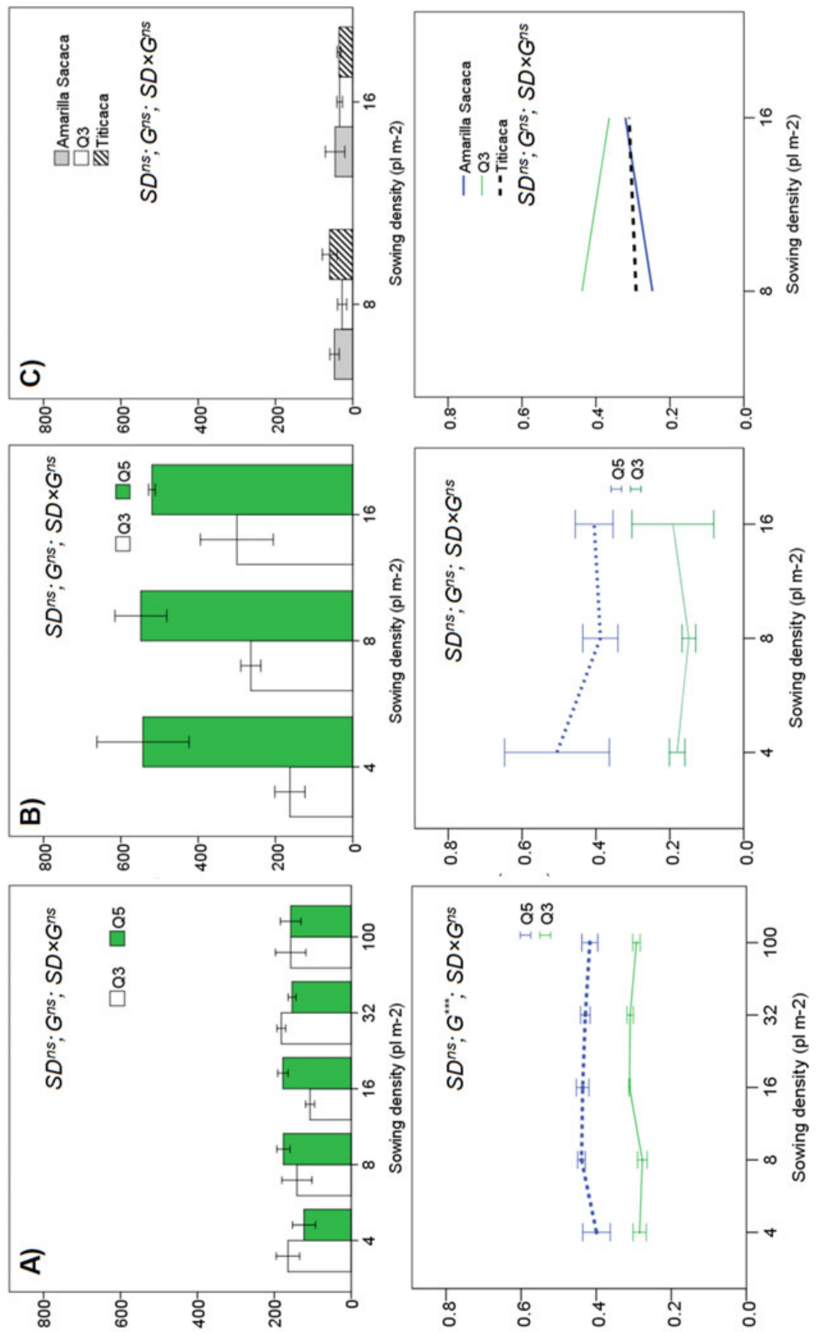

Fig. 6.3 Seed yield and harvest index of four quinoa genotypes at different sowing densities in three localities: Dubai (**a**), Al Dhaid (**b**) and Abu Dhabi (**c**). ***, **, * significant at $P < 0.001$, $P < 0.01$, $P < 0.05$ and (NS) not significant, (G) quinoa genotype, (S.D.) sowing density

Table 6.3 Seed yield and harvest index of quinoa genotypes at different sowing densities

	Dubai			Al Dhaid			Abu Dhabi		
Seed yield (g m^{-2})									
Source of variation	d. f.	MQ	vc (%)	d. f.	MQ	vc (%)	d. f.	MQ	vc (%)
S.D.	4	928.5^{NS}	16.3	2	6088.5^{NS}	1.5	1	248.0^{NS}	16.9
G	1	522.6^{NS}	9.2	1	391,332.3^{NS}	96.1	2	706.5^{NS}	48.3
S.D. × G	4	4248.3^{NS}	74.5	2	9794.0^{NS}	2.4	2	509.2^{NS}	34.8
Error	30	2594.0		12	14,938.2		18	898.3	
Harvest index									
S.D.	4	0.00^{NS}	0.6	2	0.008^{NS}	2.5	1	0.00^{NS}	0.0
G	1	0.17***	98.8	1	0.303^{NS}	95.9	2	0.03^{NS}	74.4
S.D. × G	4	0.00^{NS}	0.6	2	0.005^{NS}	1.6	2	0.01^{NS}	25.6
Error	30	0.00		12	0.006		18	0.05	

d.f., degrees of freedom; MQ, mean sum squares; vc (%) relative contribution of individual factors and their interactions to total variation, ***, **, * significant at $P < 0.001$, $P < 0.01$, $P < 0.05$ and (NS) not significant, (G) quinoa genotype, (S.D.) sowing density

than environments are the major determinant of harvest index for quinoa crops. Hot temperatures during flowering (Table 6.2, Fig. 6.1) and seed development can contribute to substantial variation in HI. Playing with sowing density (number of plants per square metre) had no effect on quinoa, but there were differences between two genotypes in Dubai.

Two quinoa lines ICBA-Q3 and ICBA-Q5 have produced grains, different for Dubai and Al Dhaid for the quantity of irrigation. In contrast in Abu Dhabi, the yield was very low. ICBA-Q5 quinoa line had higher grain yield than ICBA-Q3. In phenological evaluation made to ICBA-Q5 for this experiment and in Al Dhaid (another trial on sowing dates not published yet), this genotype had earliest flowering time than ICBA-Q3. Production of grain for the new introduced genotypes Titicaca and Amarilla Sacaca in Abu Dhabi was low under two sowing densities. Although these last genotypes have reported as earliest in growing in trials undertaken in Eastern and South Africa rural communities (Mukankusi et al. 2016) and Northeast and North Africa (Dost 2016).

6.3.4 Aerial and Underground Biomass

Photosynthesis is fundamental to plant productivity; many other factors modify the magnitude of productivity attained in the field. The quantitative relationship between photosynthesis and plant productivity should be considered first. Economic yield is the amount of this productivity which is partitioned into the useful or harvested portion of the crop, e.g. the grain of cereals and the trunks of timber trees of the shoots of herbage crops. The proportion of total biomass production which is invested into the harvested parts of the plant is termed the harvest index. Quinoa

ICBA-Q3 line in average for the five sowing densities had highest root biomass than ICBA-Q5 in Dubai and Al Dhaid and not in Abu Dhabi (Fig. 6.4c). Similar trend had shoot biomass when ICBA-Q3 had highest biomass in every one of the localities. Root and shoot biomass were different among genotypes, nevertheless not among sowing densities (Table 6.4).

Highest aerial dry biomass had the genotype ICBA-Q3 in Al Dhaid by 1406.7 g m^{-2} (16 pl m^{-2}) as this relation was plants in a square metre (Fig. 6.4). Shoot dry biomass was significantly different between two genotypes in Dubai ($p < 0.05$) and not in Abu Dhabi. Although less water was applied for the same genotype. Similar performance had dry root biomass in Al Dhaid. The quinoa genotype ICBA-Q3 had 153 g m^{-2} but not different among sowing density. Quinoa genotype ICBA-Q3 was reported as well in the agricultural season of 2013–2014 and 2014–2015 (Rao and Shahid 2013; Choukr-Allah et al. 2016).

Sowing density had no effect on the aerial and ground biomass in the three localities. However, there were significant difference between two quinoa lines in Dubai for dry shoot biomass ($p < 0.05$) and root biomass ($p < 0.001$). Distance between plants belonging to different treatments had not affected in the production of biomass. In Al Dhaid showed a positive proportional relation of plant number per area. The selected quinoa lines are from lowland and subtropical region where develop and produce high yield in biomass comparing to quinoa from highland (Altiplano). Between two lines there were differences in shoot and root biomass in Al Dhaid, the increasing is proportional as number per plants increase per area (Fig. 6.4). Spehar and da Silva Rocha (2009) stressed out that biomass and grain yield are interdependent and can affect harvest index. Quinoa line ICBA-Q5 can respond positively to the use of organic amendments for increasing yield in biomass and grain in sandy poor soil (Gill et al. 2017).

6.3.5 Plant Height and Stem Diameter

In general average among localities, plant height was higher for ICBA-Q3 and shorter for Titicaca genotype. In Dubai sowing density had not effect on height amid two quinoa genotypes, similar in Al Dhaid. In contrast, there were significant differences among two sowing densities in Abu Dhabi among three genotypes. Sowing densities due to distance between plants in the lines and plants per square metre had significant effect in Dubai for ICBA-Q3.

Sowing density did not have any significant effect on plant height of quinoa genotypes in the localities, and stem diameter only had effect in Al Dhaid ($p < 0.05$) (Table 6.5). In contrast, there were significant differences ($p < 0.001$) among plant height in quinoa genotypes in Dubai and Al Dhaid and not in Abu Dhabi. There was a positive relation between number of plants per square metre and stem diameter in Al Dhaid, as density increases as stem diameter diminishes.

ICBA-Q3 line of quinoa had highest height of quinoa in Dubai and Al Dhaid, in both localities, there were significant differences in length of stem the same for

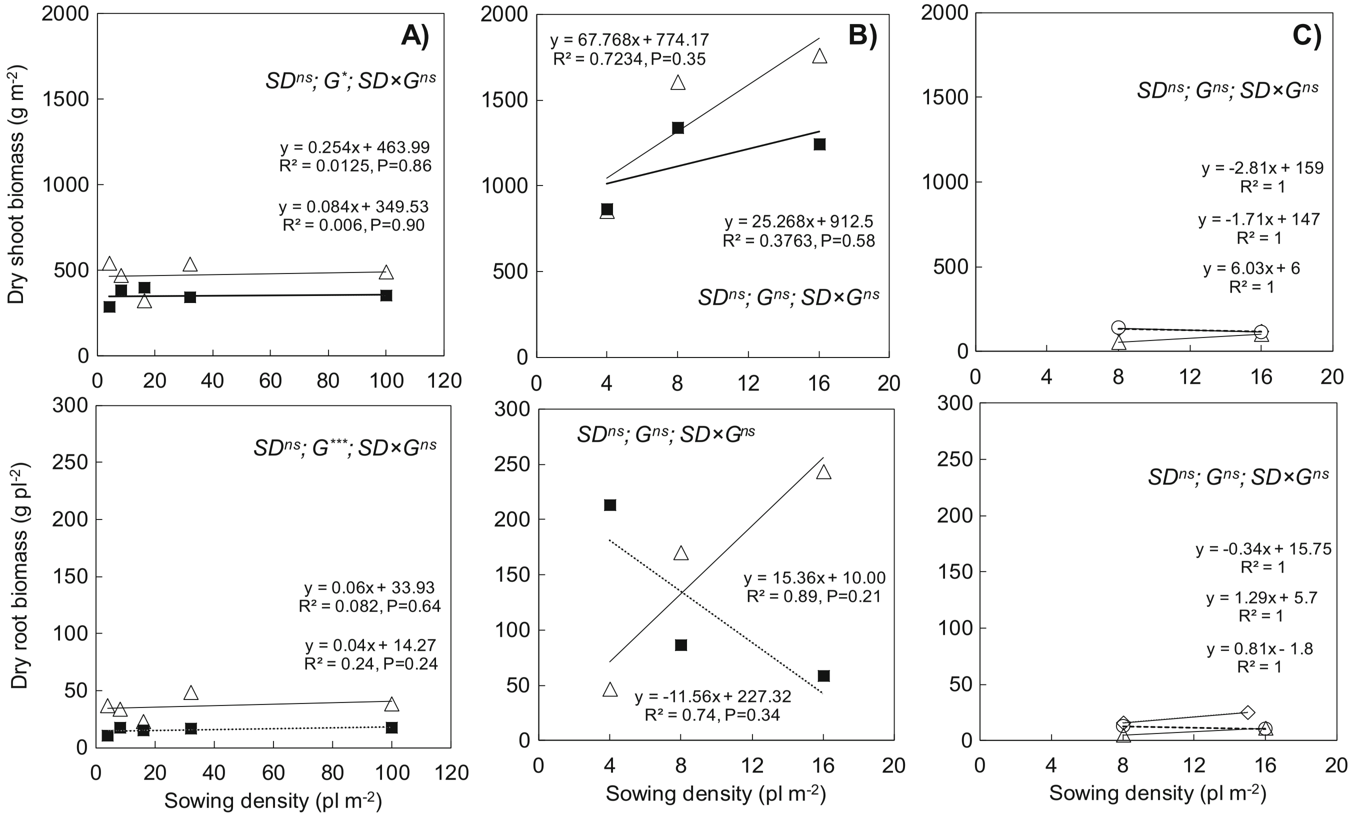

Fig. 6.4 Dry shoot and root biomass of four quinoa genotypes at different sowing densities in three localities: Dubai (**a**), Al Dhaid (**b**) and Abu Dhabi (**c**). ***, **, * significant at $P < 0.001$, $P < 0.01$, $P < 0.05$ and (NS) not significant, (G) quinoa genotype, (S.D.) sowing density. Where quinoa genotypes are denoted as: ICBA-Q3 (*triangle*), ICBA-Q5 (*Square*), Titicaca (*Circle*) and Amarilla Sacaca (*Rhombus*)

Table 6.4 Dry shoot and root biomass of genotypes at different sowing densities

	Dubai			Al Dhaid			Abu Dhabi		
Dry shoot biomass (g m^{-2})									
Source of variation	d. f.	MQ	vc (%)	d. f.	MQ	vc (%)	d. f.	MQ	vc (%)
S.D.	4	7847.9^{NS}	4.3	2	795,004.2^{NS}	66.2	1	96.0^{NS}	1.1
G	1	143,832.0*	78.3	1	300,312.5^{NS}	25.0	2	6003.4^{NS}	66.2
S.D. × G	4	31,995.8^{NS}	17.4	2	106,079.2^{NS}	8.8	2	2975.4^{NS}	32.8
Error	30	19,514.9		12	269,056.9		18	7091.2	
Dry root biomass (g m^{-2})									
S.D.	4	210.1^{NS}	4.6	2	945.6^{NS}	1.7	1	126.0^{NS}	24.4
G	1	4235.4***	91.7	1	5183.0^{NS}	9.4	2	303.0^{NS}	58.7
S.D. × G	4	172.2^{NS}	3.7	2	49,058.5^{NS}	88.9	2	86.8^{NS}	16.8
Error	30	125.7		12	22,947.8		18	190.3	

d.f., degrees of freedom; MQ, mean sum squares; vc (%) relative contribution of individual factors and their interactions to total variation, ***, **, * significant at $P < 0.001$, $P < 0.01$, $P < 0.05$ and (NS) not significant, (G) quinoa genotype, (S.D.) sowing density

Table 6.5 Plant height and stem diameter of genotypes at different sowing densities

	Dubai			Al Dhaid			Abu Dhabi		
Plant height (cm)									
Source of variation	d. f.	MQ	vc (%)	d. f.	MQ	vc (%)	d. f.	MQ	vc (%)
S.D.	4	231.8^{NS}	1.7	2	11.7^{NS}	0.1	1	271.5^{NS}	40.9
G	1	12,970.8***	96.4	1	8439.2***	99.7	2	95.1^{NS}	14.3
S.D. × G	4	258.6^{NS}	1.9	2	17.0^{NS}	0.2	2	297.4^{NS}	44.8
Error	30	222.9		12	330.4		9	205.8	
Stem diameter (mm)									
S.D.	4	8.7^{NS}	9.0	2	37.9*	61.3	1	0.75^{NS}	13.5
G	1	81.0***	83.8	1	21.4^{NS}	34.6	2	2.80^{NS}	50.2
S.D. × G	4	7.0^{NS}	7.2	2	2.6^{NS}	4.1	2	2.02^{NS}	36.3
Error	30	4.0		12	8.2		9	1.74	

d.f., degrees of freedom; MQ, mean sum squares; vc (%) relative contribution of individual factors and their interactions to total variation, ***, **, * significant at $P < 0.001$, $P < 0.01$, $P < 0.05$ and (NS) not significant, (G) quinoa genotype, (S.D.) sowing density

ICBA-Q5 ($p < 0.001$) (Fig. 6.5a and b). However, sowing density or number of plants per square metre did not affect plant height.

Sowing density only had effect ($p < 0.05$) in stem diameter in the locality of Al Dhaid, and not in Dubai and Abu Dhabi. There was a strong relationship explained in this locality. As more number in plants increase as stem diameter will diminish. In contrast, there were significant differences between two quinoa lines ($p < 0.001$) in stem diameter in Dubai. These results illustrate how quinoa reacts.

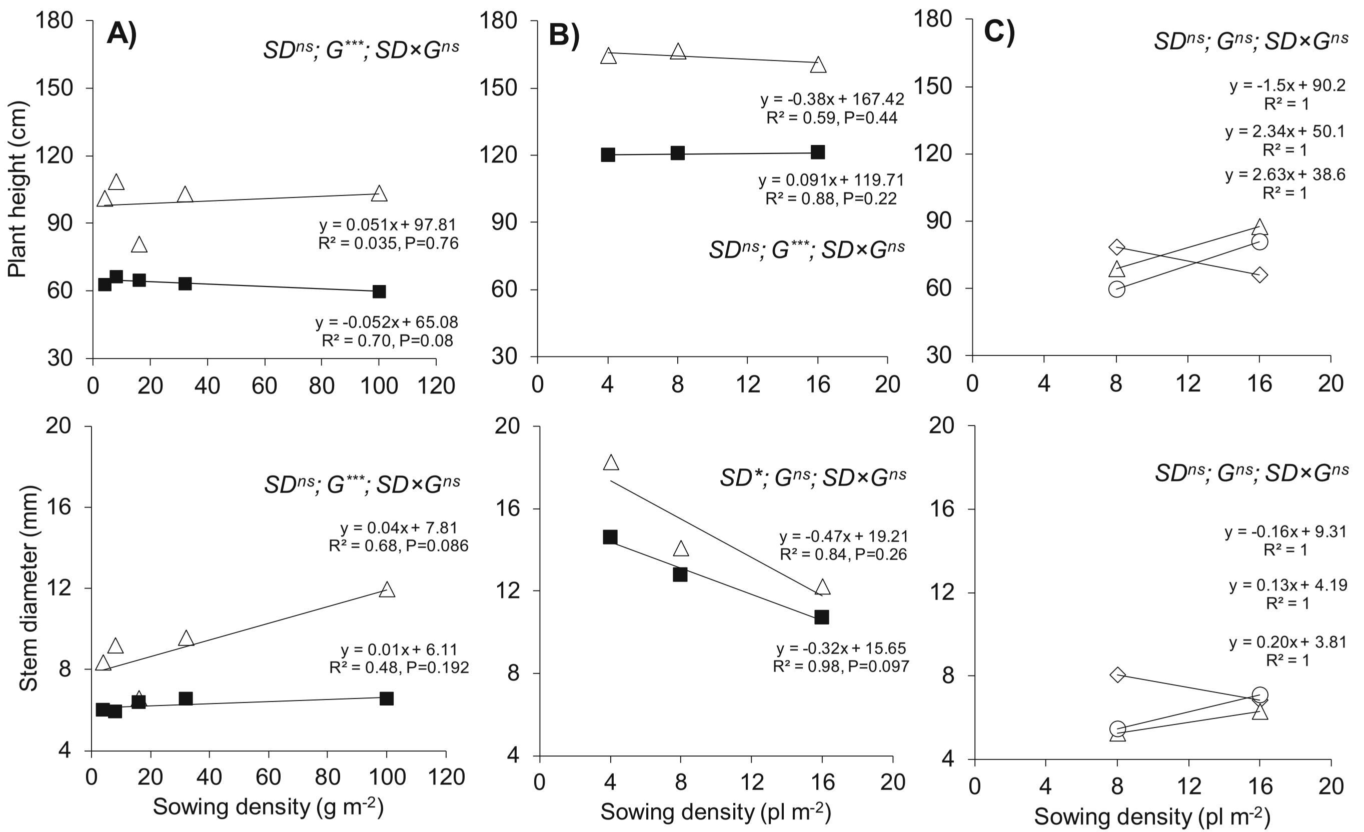

Fig. 6.5 Plant height and stem diameter of four quinoa genotypes at different sowing densities in three localities: Dubai (**a**), Al Dhaid (**b**) and Abu Dhabi (**c**). ***, **, * significant at $P < 0.001$, $P < 0.01$, $P < 0.05$ and (NS) not significant, (G) quinoa genotype, (S.D.) sowing density. Where quinoa genotypes are denoted as: ICBA-Q3 (*Triangle*), ICBA-Q5 (*Square*), Titicaca (*Circle*) and Amarilla Sacaca (*Rhombus*)

6.4 Conclusions

Quinoa ICBA-Q3 and ICBA-Q5, with biological cycle of 130, 120 and 128 days in three localities of United Arab Emirates, showed no effect of sowing density on seed yield, harvest index and plant height. Stem diameter showed reduction with increasing density (number of plants per square metre) after 16 pl m^{-2} (distance between plants of 12 cm). Plants at low densities tend to increase branching, to fill the gaps and to delay maturity. ICBA-Q5 produce higher grain yield in Dubai and Al Dhaid at experimental conditions. It should be optimized to field and farmer conditions, because drip irrigation is different, and management are according to farming systems. Under the growing period in the three localities, the average temperatures were appropriate for the four quinoa genotypes. Although quinoa can perform well in improved native sandy soils with organic amendments, our study showed that quinoa produce biomass and grain at low sandy fertility soil. Post-evaluation should be done in fertility mobilization to establish with organic amendments or crop rotations to keep a healthy soil. During the growing period of quinoa in the three localities not pest and diseases in the quinoa genotypes were reported. Climate in the three localities had similar patterns and conditions of meteorological variables during the growing season of quinoa. Appropriate time for growing quinoa is 5 months from October to April where average temperatures are around 22 °C.

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References

Adolf V, Jacobsen S-E, Shabala S (2013) Salt tolerance mechanisms in quinoa (*Chenopodium quinoa* Willd.). Environ Exp Bot 92:43–54. https://doi.org/10.1016/j.envexpbot.2012.07.004

Adolf V, Shabala S, Andersen M, Razzaghi F, Jacobsen S-E (2012) Varietal differences of quinoa's tolerance to saline conditions. Plant Soil 357:117–129. https://doi.org/10.1007/s11104-012-1133-7

Alandia G, Rodriguez JP, Jacobsen S-E, Bazile D, Condori B (2016) A new face of quinoa production: challenges for the Andean region. In: International conference quinoa for future food and nutrition security in marginal environments, December 6–8, 2016 Dubai, United Arab Emirates. ICBA. Dubai, ICBA, p. 29–30

Bazile D, Pulvento C, Verniau A, Al-Nusairi MS, Ba D, Breidy J, Hassan L, Mohammed MI, Mambetov O, Otambekova M, Sepahvand NA, Shams A, Souici D, Miri K, Padulosi S (2016) Worldwide evaluations of quinoa: preliminary results from post international year of quinoa FAO projects in nine countries. Front Plant Sci 7:850. https://doi.org/10.3389/fpls.2016.00850

Bertero HD, King RW, Hall AJ (1999) Photoperiod-sensitive development phases in quinoa (*Chenopodium quinoa* Willd.). Field Crop Res 60:231–243

Bertero HD, De la Vega AJ, 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 reveals by pattern analysis of international multi-environmental trials. Field Crop Res 89:299–318. https://doi.org/10.1016/j.fcr.2004.02.006

Choukr-Allah R, Rao NK, Hirich A, Shahid M, Alshankiti A, Toderich K, Gill S, Butt KUR (2016) Quinoa for marginal environments: toward future food and nutritional security in MENA and Central Asia regions. Front Plant Sci 7:346. https://doi.org/10.3389/fpls.2016.00346

Christensen SA, Pratt DB, Nelson PT, Stevens MR, Jellen EN, Coleman CE, Fairbanks DJ, Bonifacio A, Maughan PJ (2007) Assessment of genetic diversity in the USDA and CIP-FAO international nursery collections of quinoa (*Chenopodium quinoa* Willd.) using microsatellite markers. Plant Genetic Res Character Utiliz 5(2):82–95. https://doi.org/10.1017/S1479262107672293

Christiansen JL, Jacobsen S-E, Jørgensen ST (2010) Photoperiodic effect on flowering and seed development in quinoa (*Chenopodium quinoa*). Acta Agriculturae Scandinavica Section B – Soil and Plant Science 60:539–544. https://doi.org/10.1080/09064710903295184

Croitoru AE, Piticar A, Imbroane AM, Burada DC (2012) Spatiotemporal distribution of aridity indices based on temperature and precipitation in the extra-Carpathian regions of Romania. Theor Appl Climatol 112:597. https://doi.org/10.1007/s00704-012-0755-2

De Martonne E (1925) Traite de Geographie Physique, Vol I: Notions generales, climat, hydrogeographie. Geogr Rev 15(2):336–337

Dost M (2016) Potential of quinoa production in near east and North Africa region. In: International conference quinoa for future food and nutrition security in marginal environments, December 6–8, 2016 Dubai, United Arab Emirates. ICBA. Dubai, ICBA, p. 28

Estrada R, Gonza VA, Altamirano H, Arana J (2011) Quinua INIA 427 Amarilla Sacaca: variedad con Buena productividad, sanidad y adaptación. (in Spanish). Technical Newsletter. repebis.upch.edu.pe/articulos/agroinnova/v2n11/a6.pdf

Fita A, Rodriguez-Burruezo A, Boscalu M, Prohens J, Vicente O (2015) Breeding and domesticating crops adapted to drought and salinity: a new paradigm for increasing food production. Front Plant Sci 6:978. https://doi.org/10.3389/fpls.2015.00978

Gill S, Alshankiti A, Shahid SA, Rodriguez JP (2017) Organic amendments effect on soil health and alternative crops productivity in marginal desert land of United Arab Emirates. In: Hirich A, Redouane C, Ragab R (eds) Emerging research in alternative crops under marginal environment. Springer, Netherlands

Glenn EP, Anday T, Chaturvedi R, Martinez-Garcia R, Pearlstein S, Soliz D (2013) Three halophytes for saline-water agriculture: an oilseed, a forage and a grain crop. Environ Exp Bot 92:110–121. https://doi.org/10.1016/j.envexpbot.2012.05.002

Gómez-Pando LR, Álvarez-Castro L, Eguiluz-de la Barra A (2010) Short communication: effect of salt stress on Peruvian Germplasm of *Chenopodium quinoa* Willd.: a promising crop. J Agron Crop Sci 196(5):391–396

Hamdy A (2016) Quinoa and its potential to grow under water scarcity and salt stress conditions: promising research findings. In: International conference quinoa for future food and nutrition security in marginal environments, December 6–8, 2016 Dubai, United Arab Emirates. ICBA. Dubai, ICBA, p. 23

Hirich A, Choukr-Allah R (2016) Phenotyping the combined effect of heat and water stress on. In: International conference quinoa for future food and nutrition security in marginal environments, December 6–8, 2016 Dubai, United Arab Emirates. ICBA. Dubai, ICBA, p. 40

Huang JZ, Shrestha A, Tollenaar M, Deen W (2001) Effect of temperature and photoperiod on the phenological development of common lambsquarters. Weed Sci 49:500–508

Hunter MC, Smith RG, Schipanski ME, Atwood LW, Mortensen DA (2017) Agriculture in 2050: recalibrating targets for sustainable intensification. BioScience 67(4):386–391. https://doi.org/10.1093/biosci/bix010

IBM Corp (2016) IBM SPSS statistics for windows, version 24.0. IBM Corp, Armonk, NY

ICBA (2007) Annual Report 2006 (1426-27H). International Center for Biosaline Agriculture, Dubai, UAE. https://www.biosaline.org/sites/default/files/Annualreportpdf/AR2007-Eng.pdf. Accessed 16 July 2018

Jacobsen S-E, Bach A (1998) The influence of temperatures on seed germination rate in quinoa (*Chenopodium quinoa* Willd.). Seed Sci Technol 26:515–523

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

Jacobsen S-E (2016) The worldwide potential of quinoa as a new climate-proof crop. In: International conference quinoa for future food and nutrition security in marginal environments, December 6–8, 2016 Dubai, United Arab Emirates. ICBA. Dubai, ICBA, p. 5

Jarvis A, Upadhyaya H, Gowda CLL, Aggarwal PK, Fujisaka S, Anderson B (2015) Plant genetic resources for food and agriculture and climate change. In: coping with climate change – the roles of genetic resources for food and agriculture (FAO 2015). Rome, pp. 9–21 (Available at http://www.fao.org/3/a-i3866e.pdf)

Koyro H-W, Khan MA, Lieth H (2011) Halophytic crops: a resource for the future to reduce the water crisis. Emir J Food Agric 23(1):01–16. https://doi.org/10.9755/ejfa.v23i1.5308

Lesjak J, Calderini DF (2017) Increased night temperature negatively affects grain yield, biomass and grain number in Chilean quinoa. Front Plant Sci 8:352. https://doi.org/10.3389/fpls.2017.00352

McMaster GS, Wilhelm WW (1997) Growing degree-days: one equation, two interpretations. Agric For Meteorol 87:291–300. https://doi.org/10.1016/S0168-1923(97)00027-0

Mukankusi C, Amongi W, Berhanu F, Wanderi S, Rono BK, Okee J, Okiro AO, Mwaba C, Kooma E, Abang M (2016) Adaptability of quinoa (*Chenopodium quinoa* Willd.) in eastern and southern Africa: potential implications for food security and climate change adaptation. In: International conference quinoa for future food and nutrition security in marginal environments, December 6–8, 2016 Dubai, United Arab Emirates. ICBA. Dubai, ICBA, p. 23

Pulodov MP, Miminshoeva ZM, Ergashev M, Pulodov FP, Nekushoeva G (2016) Agronomical evaluation of *Chenopodium quinoa* Willd. Under rainfed piedmont environments in Tajikistan. In: International conference quinoa for future food and nutrition security in marginal environments, December 6–8, 2016 Dubai, United Arab Emirates. ICBA. Dubai, ICBA, p. 35

Rao NK, Shahid M, Shahid SA (2009) Alternative crops for diversifying production systems in the Arabian peninsula. Arab Gulf Journal of Scientific Research 27(4):195–203

Rao NK, Shahid M (2012) Quinoa – a promising new crop for the Arabian peninsula. American-Eurasian J Agric Environ Sci 12(10):1350–1355. https://doi.org/10.5829/idosi.aejaes.2012.12.10.1823

Rao NK, Shahid M (2013) Neglected and underutilized crops for sustainable agriculture in marginal areas. In: Hall R, Rudebjer P (eds) Proceeding of 3rd international conference on neglected and underutilized species: for a food-secure Africa, held in Accra, Ghana, 25-27 September 2013. Theme 1C: resilience of agricultural and livelihood systems: climate change, pp. 130–139

Rao NK (2016) Quinoa: a future–proof crop for climate smart agriculture. In: Choukr-Allah R (ed) Global forum for innovations in agriculture–2016. Abu Dhabi, UAE

Rodriguez JP, Rahman H, Thushar S, Singh RK (2020) Healthy and resilient cereals and pseudo-cereals for marginal agriculture: molecular advances for improvingnutrient bioavailability. Front Genet 11. https://doi.org/10.3389/fgene.2020.00049

Sepahvand NA, Miri Kh, Molaei A (2016) Quinoa research and prospect in in Iran. In: international conference quinoa for future food and nutrition security in marginal environments, December 6–8, 2016 Dubai, United Arab Emirates. ICBA. Dubai, ICBA, p. 35

Spehar CR, da Silva Rocha JE (2009) Effect of sowing density on plant growth and development of quinoa, genotype 4.5, in the Brazilian Savanah highlands. Biosci J Uberlandia 25(4):53–58

Statista Report (2016) Quinoa market - statistics & facts. Available: https://www.statista.com/topics/2813/quinoa-market/

Villa DYG, Russo L, Kerbab KM, Rastrelli L (2014) Chemical and nutritional characterization of *Chenopodium pallidicaule* (cañihua) and *Chenopodium quinoa* (quinoa) seeds. Emir J Food Agric 26(7):609–615

Chapter 7
Phenotyping the Combined Effect of Heat and Water Stress on Quinoa

Hirich Abdelaziz and Choukr-Allah Redouane

Abstract Quinoa is a pseudo-cereal crop that originates from Latin America and has been shown to be resistant to various abiotic stresses including water, salinity, frost, and heat stress. Quinoa was subjected, in the beginning of twenty-first century, to a large number of researches in all parts of the world including GCC (Gulf Cooperation Council) region which was characterized by a harsh climatic condition, excessive heat, and water scarcity. This experiment was conducted in the International Center for Biosaline Agriculture, UAE, in order to phenotype the responses of quinoa to heat and water stress. The experiment consisted of a germination test and pot trial. The germination test was performed for five quinoa lines under five temperatures (2, 10, 22, 30, 42 °C). Obtained results indicate that germination velocity increased with increased temperature up to 30 °C then decreased under heat stress (42 °C). Germination rate followed the same trend with nonsignificant difference between temperatures below 30; however, under 42 °C, germination rate has been reduced by 13% compared to 22 °C.

The pot experiment was conducted during the period of May to August 2016 aimed to phenotype 5 quinoa lines under four different environments: greenhouse cooled at 24 °C, greenhouse cooled at 29 °C, greenhouse cooled at 35 °C, and open-air conditions (T max exceeds 42 °C). Quinoa was also subjected to water stress (50% of full irrigation) during vegetative growth stage. Several morphological and physiological traits have been monitored including plant height, stem diameter, number of primary branches, leaf architecture, number of primary panicle, panicle weight, shoot weight, seed yield, seed size, days to flowering, days to maturity, stomatal conductance, and leaf temperature. It has been shown that heat and water stress affected all phenotypic and physiological traits, but a more pronounced effect was observed under heat stress compared to water stress. Heat and water stress

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affected negatively and delayed the flowering and maturity. Q5 and NSL 106399 lines flowered and matured early compared to other lines. Flowering has been inhibited under greenhouse cooled at 35 °C and open-field conditions due to excessive heat causing pollen sterility. The highest growth and productivity performances of quinoa lines were obtained under greenhouse cooled at 24 °C. Q5 and NSL 106399 lines were shown to be the most productive and resistant to heat stress. Stomatal conductance as physiological parameter was affected negatively by both heat and water stress. There was a reduction of more than 90% in average under open-field conditions compared to greenhouse cooled at 24 °C.

The finding indicates that heat stress is a limiting factor for quinoa adaptation under GCC conditions. It is recommended to grow quinoa during the mild season (October to April). Temperature exceeding 30 °C during flowering and grain filling stages was shown to be, agronomically and economically, the threshold of quinoa production where beyond this threshold seed yield is greatly affected.

Keywords GCC region · Irrigation · Yield · Sowing · Stomatal conductance · Plant architecture

7.1 Introduction

As well-known climate change is exhibited by an increase in temperature and reduction in rainfall in many places especially the marginal environments. Therefore, this is considered as major threat to crop production and food security (Hirich et al. 2016; Seif-Ennasr et al. 2016). Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. The IPCC (2014) report clearly indicates that the increase of global mean surface temperature by the end of the twenty-first century (2081–2100) relative to 1986–2005 is likely to be 0.3 °C to 1.7 °C under RCP2.6, 1.1 °C to 2.6 °C under RCP4.5, 1.4 °C to 3.1 °C under RCP6.0, and 2.6 °C to 4.8 °C under RCP8.5 emission scenario. This rise in the temperature is posing prominent effects on crop production, especially in terms of exasperating the related effects of drought and salinity. Food security in marginal environments which already suffer from physical problems related to drought and salinity is now facing many challenges in the coming decades including the rapid population growth, limited water resources, degraded lands, social insecurity, etc. (Wheeler and Von Braun 2013).

Alternative crops can contribute to crop diversification in agricultural production systems and enhance human health and food security by providing a diverse array of food crops (Kim 2016). Alternatives can provide a judicious solution within the context of climate change adaptation as most of them are climate proof and resilient crops, and some species can tolerate salinity, drought, and heat as the case of quinoa.

Quinoa is a pseudo-cereal crop that originates from Latin America and considered one of the most nutritious food crops currently known, and the nutritive properties of the crop are seen as a mean to fight malnutrition globally (Choukr-allah et al. 2016).

Quinoa is considered in human nutrition for its high protein content and balance amino acid with high amount of lysine and methionine, and high amount of fiber and minerals such as calcium and iron (Abugoch James 2009). It is rich in antioxidants such as polyphenols (Nsimba et al. 2008). Quinoa is gluten-free and suitable for celiac patients, and whole grain consumption prevents type 2 diabetes and because of low glycemic index can replace common cereals in diabetes diet (de Munter et al. 2007; Zevallos et al. 2015). Quinoa was subjected, in the beginning of twenty-first century, to a large number of researches in all parts of the world including GCC (Gulf Cooperation Council) region which was characterized by a harsh climatic condition, excessive heat, and water scarcity (Choukr-allah et al. 2016). Quinoa has been shown to be resistant to various abiotic stresses including water (Fghire et al. 2015; Hirich 2013; Hirich et al. 2013, 2012; Geerts et al. 2009, 2008; Filali et al. 2017), salinity (Hirich et al. 2014b, c; Koyro et al. 2008; Eisa et al. 2012; Koyro and Eisa 2008; Razzaghi et al. 2012; Shabala et al. 2013; Yazar et al. 2015; Jacobsen et al. 2000), frost (Bonifacio 2005; Jacobsen et al. 2005, 2007; Winkel et al. 2009), and heat stress (Bazile et al. 2016; Bertero 2001).

Scientists have long known that plants are often subjected to simultaneous occurrence of several abiotic stresses, rather than a particular stress condition, for example salinity and heat stress always lead to water stress (BarnabÁS et al. 2008). The combination of drought and heat stress represents an excellent example of two different abiotic stress conditions that occur in the field simultaneously (Prasad et al. 2008; Jiang and Huang 2000). Heat stress to varying degrees at different phenological stages causes a substantial yield reduction (Gibson and Paulsen 1999; Hasanuzzaman et al. 2013), primarily because of growth acceleration, reduction in duration of phasic developmental stages, and carbon starvation owing to reduced net assimilation (Hirich et al. 2014a). The probability of heat stress around flowering which results in considerable yield loss is also predicted to increase significantly in coming years (Farooq et al. 2011). Exposure of plants to drought stress substantially decreases the leaf water potential, relative water content, and transpiration rate, with a concomitant increase in leaf temperature (Chaves et al. 2002). Although components of plant water relations are affected by reduced availability of water, stomatal opening and closing is more strongly affected (Radin 1984).

The objective of this experiment is to evaluate the effect of different temperatures on quinoa seed germination as well as to phenotype 5 quinoa accessions grown under four different environments and two irrigation levels.

7.2 Materials and Methods

Germination test and pot trials under greenhouse conditions were carried out in the experimental station of the International Center for Biosaline Agriculture, Dubai, UAE (25.094549 N, 55.389697 E).

7.2.1 Germination Test Under Increased Temperature

7.2.1.1 Germination Conditions

The germination test was performed under controlled growth chamber in petri dishes. Five 50-seed replicates were used for each combination temperature and accession and put on filter paper in petri dishes soaked with 3 ml of distilled water. The petri dishes were sealed with Parafilm to prevent evaporation of water and kept in in the dark in a growth chamber with a relative humidity of 70%. Germination of seeds is considered when the radicle had reach at least 2 mm. Germination rate was recorded after 4, 8, 12, 24, 32, 48, 72, 96, 120, and 144 h under five temperatures, 2, 10, 22, 30, and 42 °C. The tested accessions (ICBA-Q3, AMES 13749, NSL 106399, ICBA-Q4, ICBA-Q5) were selected and adapted within the International Center for Biosaline Agriculture (Choukr-allah et al. 2016).

7.2.1.2 Germination Indexes

Various germination indexes were determined to characterize the heat tolerance including germination rate or percentage (%), coefficient of velocity of germination (CVG) (Kader and Jutzi 2004), germination rate index (GRI) (Kader 2005), and mean germination time (MGT) (Kader 2005), as follows:

$$\text{CVG}\left(\%\text{h}^{-1}\right) = \sum N_\text{i} / \sum (N_\text{i} T_\text{i}) \times 100$$

$$\text{GRI}\left(\%\text{h}^{-1}\right) = \sum \frac{N_\text{i}}{I.}$$

$$\text{MGT}\left(\text{h}\right) = \sum (N_\text{i} T_\text{i}) / \sum N_\text{i}$$

where N is the number of seeds germinated on hour i and T_i is the number of hours from sowing. The CVG gives an indication of the rapidity of germination: it increases when the number of germinated seeds increases and the time required for germination decreases. The GRI reflects the percentage of germination on each hour of the germination period. Higher GRI values indicate higher and faster germination. The lower the MGT, the faster a population of seeds has germinated (Panuccio et al. 2014).

7.2.2 Pot Trials Under Four Different Environments

7.2.2.1 Trial Conditions

The pot trial was conducted under four different environments including three greenhouses cooled at 24, 29, 35 °C, and open air. Five quinoa accessions (ICBA-

Q3, AMES 13749, NSL 106399, ICBA-Q4, ICBA-Q5) were grown in 6 liters polystyrene pots. There were four plants per pot and four pots per plot. Pots were filled by a mixture of sand, peat, and perlite. Irrigation level (50 or 100% of full irrigation) was supplied according to soil moisture content during vegetative growth stage. 100% of full irrigation (FI) was equivalent to 100% of available water content (AWC) which is 16% humidity, and 50% of full irrigation (FI) was equivalent to 50% of available water content (AWC) which is 12% humidity. Irrigation supply was controlled daily using MP306 Moisture Sensor.

7.2.2.2 Measurements

Several parameters were monitored in this experiment as follows:

- Stomatal conductance: this parameter was measured using a leaf porometer (SC-1 Leaf Porometer, Decagon) between 9 and 10 a.m.
- Morphological traits include plant height, number of primary branches, average length of primary branches, main panicle length, main panicle width, and leaf architecture (length and width). The morphological traits have been simulated using a small Matlab script in order to present them as virtual plants and to indicate the combined effect of water and heat stress on plant architecture.
- Yield and biomass: panicle dry weight, shoot dry weight, and seed weight were measured after harvesting and drying the quinoa plants.
- Flowering rate: quinoa flowering was daily monitored during flowering stage. The number of flowered plants was counted every 4 days.

7.3 Results

7.3.1 Germination Indexes

7.3.1.1 Germination Rate

Figure 7.1 presents the variation of germination rate of each accession under different temperatures. The highest germination rate was observed under both 22 and 30 °C, while the lowest rate was observed under 42 °C which indicate that heat stress affected negatively the germination rate. However low temperature at 2 °C was not reducing the germination rate but delaying the germination process as most of accessions started germination after 48 h, while under 22, 30, and 42 °C all accessions started germination after 8 h. ICBA-Q5 accessions started germination even after 4 h.

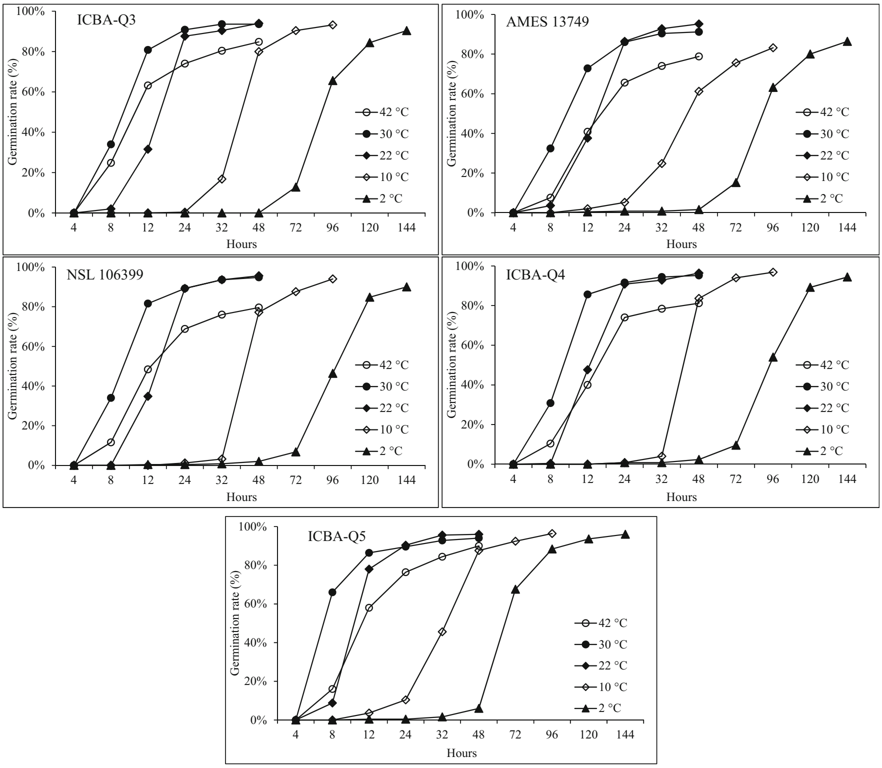

Fig. 7.1 Variation of germination rate for each quinoa accession under several temperatures

7.3.1.2 Coefficient of Velocity of Germination

Figure 7.2 presents the variation of CVG for 5 quinoa accessions under five temperatures. Obtained data indicate clearly that CVG increased with increased temperature up to 30 °C then decreased under 40 °C which indicate that heat stress and low temperature delayed the germination process. It is also obvious from Fig. 7.2 that ICBA-Q5 accession presented the highest CVG, while ICBA-Q3 presented the lowest CVG which indicates a variability in terms of germination within the tested accessions.

7.3.1.3 Germination Rate Index

Germination rate index (GRI) reflects how faster the germination process is for each accession. Figure 7.3 shows the variation of GRI for the five tested accessions under different temperatures. Presented data clearly indicate that GRI was affected by increased temperature, and the fastest germination per hour was observed under

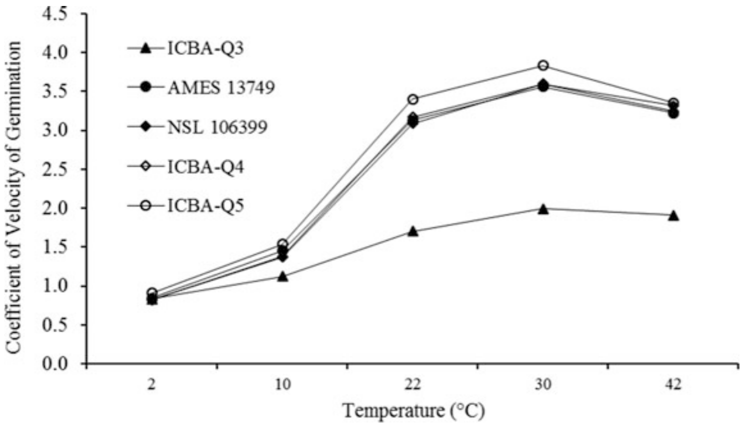

Fig. 7.2 Variation of CVG of tested accessions under different temperatures

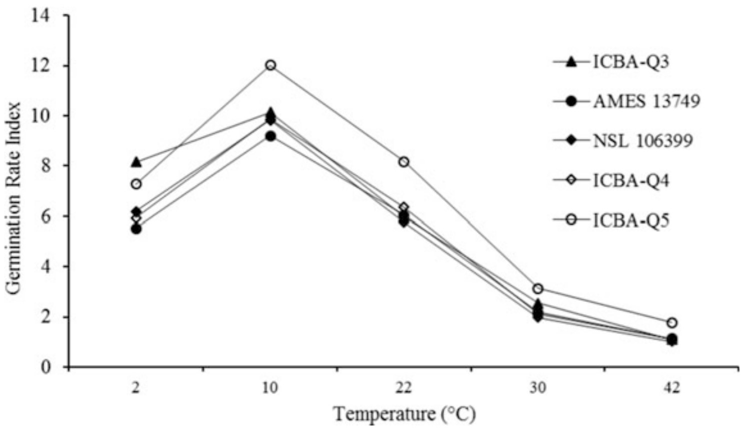

Fig. 7.3 Variation of GRI of tested accessions under different temperatures

10 °C, while the slowest germination per hour was observed under 42 °C. ICBA-Q5 accession was shown to be the fastest accession among others under most of the investigated temperatures.

7.3.1.4 Mean Germination Time

Variation of mean germination time (MGT) of tested accessions under different temperatures is presented in Fig. 7.4. Contrarily to CVG and GRI, the lower is MGT, the faster is the germination process. Similar to GRI the fastest germination for all tested accessions was observed under 10 °C. Similar to CVG, ICBA-Q3 accession presents the highest MGT among other accessions which indicate that this accession has a slow germination process compared to other accessions.

7.3.2 *Pot Trial Under Different Environments*

7.3.2.1 Air Temperature

Temperature was monitored hourly under each environment. According to Fig. 7.5, the average temperature for the whole growing period is equal to 25.2, 29.6, 33.9, and 37.8 °C. Data indicated that the cooling process in the greenhouses was more or less meeting the trial temperature requirement as the abovementioned averages are close to the set values.

7.3.2.2 Morphological Traits and Plant Architecture

Figure 7.6 presents a simulation by Matlab of several morphological traits of quinoa showing the influence of both heat and water stress on quinoa plant architecture. It is obvious that all investigated traits were affected negatively by both water and heat stress. Plant height, number of primary branches, average length of primary branches, main panicle length, and main panicle width decreased with increased air temperature and were less affected by water stress compared to heat stress. The internodes tended to be shorter under increased temperature, and this is explained by the high impact on plant height and low effect on the number of primary branches.

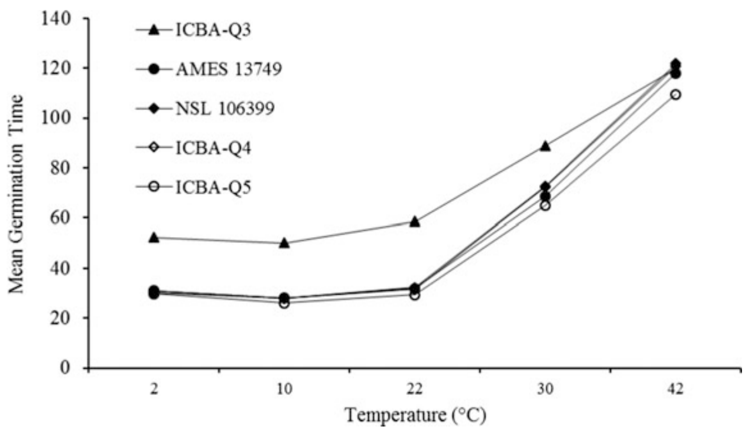

Fig. 7.4 Variation of MGT of tested accessions under different temperatures

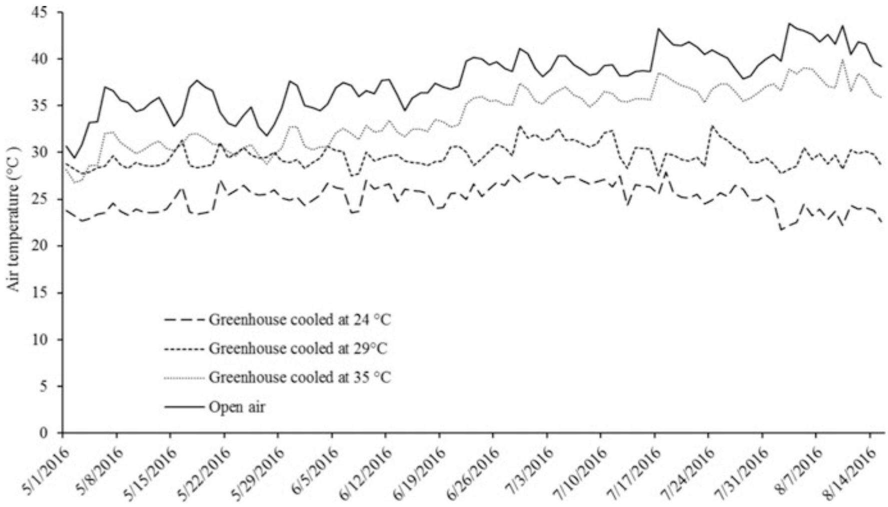

Fig. 7.5 Variation of air temperature under tested environments

7.3.2.3 Leaf Architecture

Similar to plant architecture, leaf architecture was affected by both water and heat stress with a more pronounced effect which was observed under increased temperature. Quinoa leaves tended to be larger under greenhouse cooled at 29 °C compared to greenhouse cooled at 24 °C. However, leaves were getting smaller under high temperature above 30 °C. The presented data indicate that quinoa responded to heat and water stress by reducing its leaf area to avoid water loss through transpiration process (Fig. 7.7).

7.3.2.4 Flowering

Quinoa flowering rate during the period from 30 to 50 days after sowing as influenced by both heat and water stress is presented in Table 7.1. Statistical analysis revealed a very highly significant difference ($p < 0.001$) between tested environments; however no significant difference was observed between fully irrigated and stressed plants. A high temperature more than 30 °C has affected greatly the flowering rate. Under greenhouse cooled at 35 °C conditions, there were only two accessions reaching more than 50% of flowering rate, while under open-air conditions no accession could reach 50% of germination rate which indicate that heat stress is inhibiting flowering. Under extreme heat stress, ICBA-Q5 was shown to be the most resistant to heat among other tested accessions as it showed higher flowering rate.

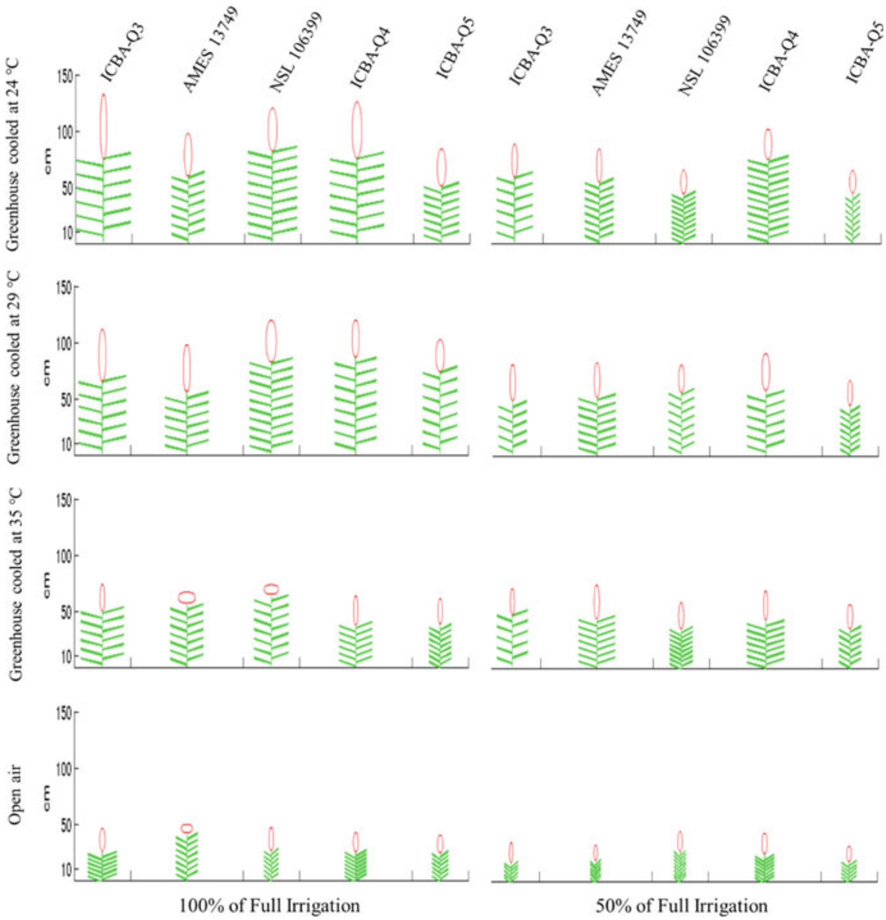

Fig. 7.6 Quinoa plant architecture as influenced by combined effect of heat and water stress

7.3.2.5 Dry Biomass and Seed Yield

The combined effect of water and heat stress on dry biomass of five quinoa accessions biomass is presented in Fig. 7.8. Statistical analysis revealed significant difference between water stresses ($p < 0.05$) and very highly significant difference between tested environments ($p < 0.001$). It is obvious from the presented results that both heat and water stress affected negatively dry biomass accumulation. The highest biomass yield under most of tested environments was obtained by ICBA-Q4 especially under extreme hot conditions (open air).

Similar to dry biomass, quinoa seed yield was affected negatively by both heat and water stress (Fig. 7.9). Presented data indicate that under greenhouse cooled at 35 °C, only NSL 106399 and ICBA-Q5 accessions could produce seed, and they are

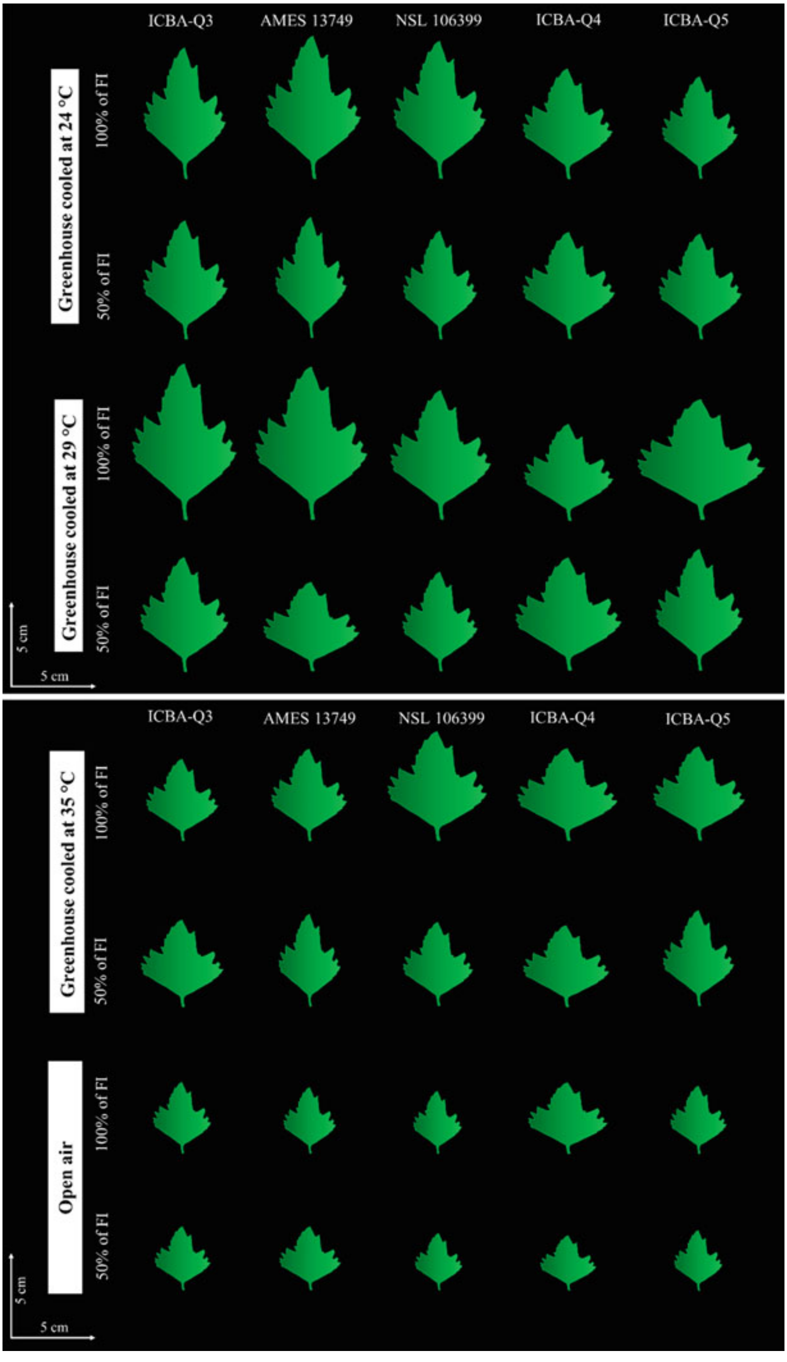

Fig. 7.7 Effect of heat and water stress on leaf architecture

Table 7.1 Evaluation of quinoa flowering as influenced by both heat and water stress

Temperature	Irrigation	Accession	30 DAS[a]	34 DAS	38 DAS	46 DAS	50 DAS
Greenhouse cooled at 24 °C	100% FI	ICBA-Q3	0%	5%	20%	**85%**	**100%**
		AMES 13749	18%	29%	**59%**	**100%**	**100%**
		NSL 106399	7%	20%	**73%**	**100%**	**100%**
		ICBA-Q4	6%	11%	22%	**83%**	**100%**
		ICBA-Q5	**70%**	**80%**	**90%**	**100%**	**100%**
	50% FI	ICBA-Q3	0%	0%	25%	**95%**	**100%**
		AMES 13749	0%	33%	**78%**	**94%**	**100%**
		NSL 106399	7%	21%	**64%**	**100%**	**100%**
		ICBA-Q4	5%	5%	5%	30%	**100%**
		ICBA-Q5	40%	40%	**75%**	**100%**	**100%**
Greenhouse cooled at 29 °C	100% FI	ICBA-Q3	8%	33%	**67%**	**100%**	**100%**
		AMES 13749	0%	0%	27%	**80%**	**100%**
		NSL 106399	40%	**85%**	**100%**	**100%**	**100%**
		ICBA-Q4	0%	0%	20%	**100%**	**100%**
		ICBA-Q5	0%	23%	**54%**	**100%**	**100%**
	50% FI	ICBA-Q3	0%	33%	**58%**	**100%**	**100%**
		AMES 13749	8%	8%	38%	**77%**	**100%**
		NSL 106399	**65%**	**100%**	**100%**	**100%**	**100%**
		ICBA-Q4	0%	5%	40%	**85%**	**100%**
		ICBA-Q5	0%	0%	0%	**90%**	**100%**
Greenhouse cooled at 35 °C	100% FI	ICBA-Q3	0%	0%	0%	0%	0%
		AMES 13749	0%	0%	7%	0%	0%
		NSL 106399	0%	6%	28%	**50%**	**94%**
		ICBA-Q4	0%	0%	0%	0%	0%
		ICBA-Q5	0%	0%	21%	**63%**	**95%**
	50% FI	ICBA-Q3	0%	0%	0%	0%	5%
		AMES 13749	0%	0%	0%	0%	0%
		NSL 106399	0%	0%	5%	16%	47%
		ICBA-Q4	0%	0%	0%	0%	0%
		ICBA-Q5	0%	0%	0%	**75%**	**100%**

(continued)

Table 7.1 (continued)

Temperature	Irrigation	Accession	30 DAS[a]	34 DAS	38 DAS	46 DAS	50 DAS
Open air	100% FI	ICBA-Q3	0%	0%	0%	0%	0%
		AMES 13749	0%	0%	0%	6%	6%
		NSL 106399	0%	5%	5%	25%	25%
		ICBA-Q4	0%	0%	0%	0%	0%
		ICBA-Q5	0%	0%	0%	45%	45%
	50% FI	ICBA-Q3	0%	0%	0%	0%	0%
		AMES 13749	0%	0%	0%	6%	6%
		NSL 106399	0%	6%	6%	11%	11%
		ICBA-Q4	0%	0%	0%	0%	0%
		ICBA-Q5	0%	0%	0%	47%	47%

[a]*DAS* days after sowing
Cells highlighted with orange color present flowering rate more than 50%

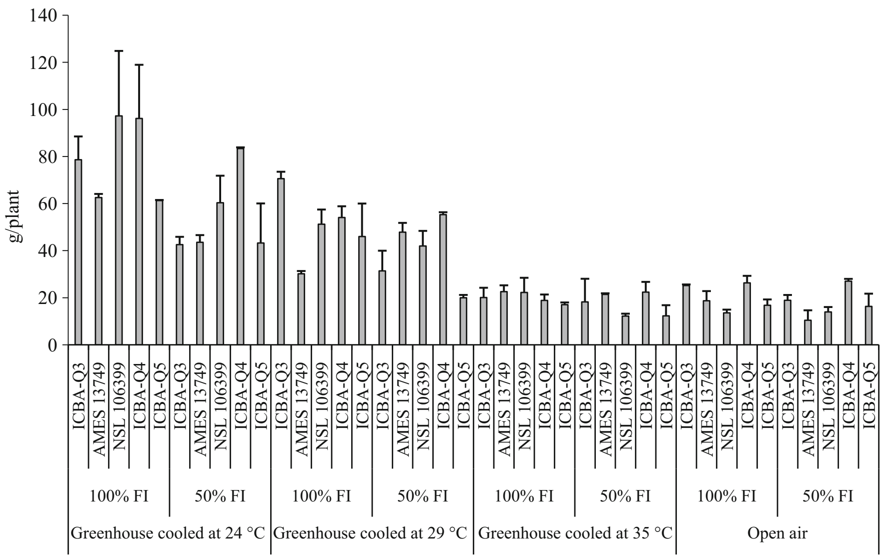

Fig. 7.8 Dry biomass of quinoa tested accessions under heat and water stress conditions

the same accession recording a high flowering rate; however, other accessions could not produce any seeds due to inhibitory effect of extreme heat. Under extreme hot conditions (open air), no accession could produce seeds. The finding indicates that NSL 106399 and ICBA-Q5 accessions are both the most resistant to heat among other tested accessions.

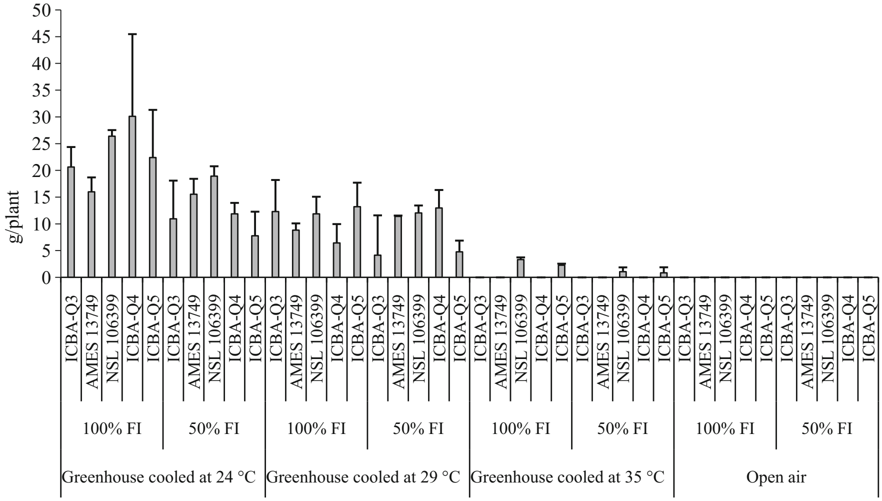

Fig. 7.9 Seed yield of quinoa tested accessions under heat and water stress conditions

7.3.2.6 Stomatal Conductance and Leaf Temperature

As expected stomatal conductance was greatly affected by both water and heat stress ($p < 0.001$). Stomatal conductance decreased with increased water stress and air temperature (Fig. 7.10). Stomatal conductance was greatly decreased dramatically with increased air temperature ($R^2 = 81\%$). A reduction rate of 49, 73, and 90% in average was recorded under greenhouse cooled at 29 °C, greenhouse cooled at 35 °C, and open air, respectively, compared to fully irrigated quinoa under greenhouse condition cooled at 24 °C. Stomatal conductance was also greatly declined under water stress. There was a reduction of 61, 70, 52, and 35% of stomatal conductance under greenhouse cooled at 24 °C, greenhouse cooled at 29 °C, greenhouse cooled at 35 °C, and open air, respectively, when plants were subjected to 50% of FI as compared to 100% FI.

Contrarily to stomatal conductance, leaf temperature increased with increased heat and water stress (Fig. 7.11) with a good linear relationship ($R^2 = 85\%$). As expected plants subjected to water stress recorded higher leaf temperature in average compared to plants which received full irrigation treatment with a difference in temperature equal to 1.7, 1.7, 3.2, and 1.2 °C under greenhouse cooled at 24 °C, greenhouse cooled at 29 °C, greenhouse cooled at 35 °C, and open air, respectively.

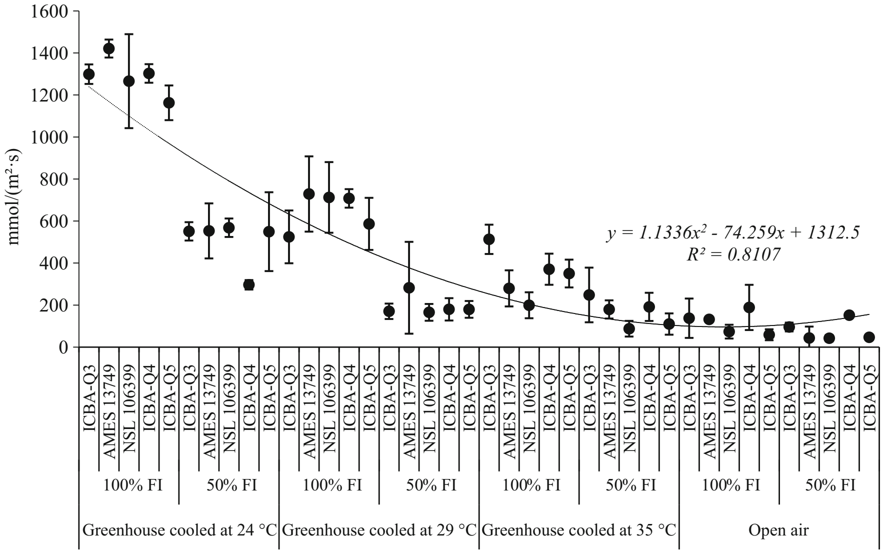

Fig. 7.10 Variation of stomatal conductance of tested accessions under water stress and different environments

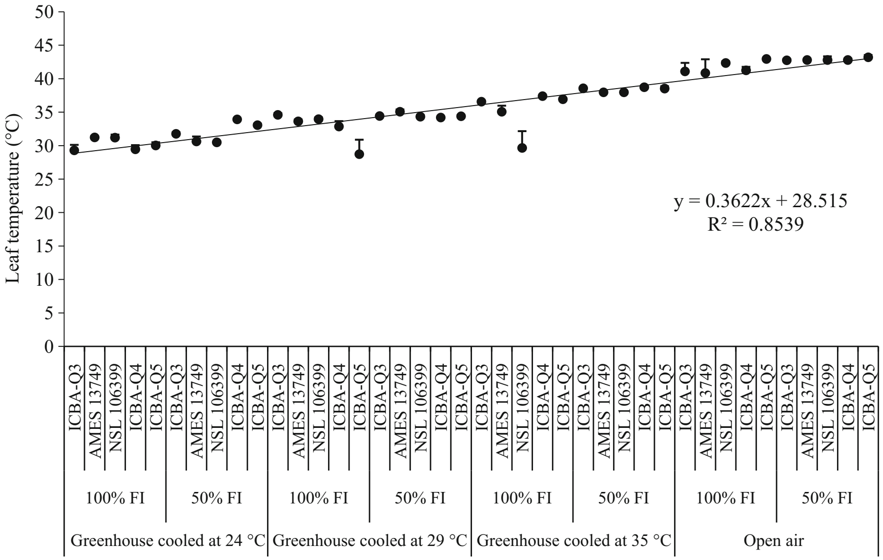

Fig. 7.11 Variation of leaf temperature of tested accessions under water stress and different environments

7.4 Discussion

This experiment including the germination test as well as the greenhouse trial allowed us to characterize most of the traits related to quinoa growth and productivity. Plants in general require a certain amount of heat to achieve its growth, development, and maturation. Growth increased with increasing air temperature up to optimum temperature, and then it starts to be negatively affected (Giovannini et al. 1990). Results in terms of quinoa germination indices showed that germination rate and velocity increased with temperature up to an optimum of 30 °C and then started to decline under extreme heat stress conditions (42 °C) as shown in Fig. 7.12.

Our finding confirms the results reported by Bois et al. (2006) who have tested ten quinoa cultivar germinations under different temperatures from 2 to 20 °C. They found that germination velocity expressed as the time needed to reach 50% of germination increased with temperature rise. With our results, the higher is the environment temperature, the less is the time to reach 50% of germination. In another study conducted by Jacobsen and Bach (1998), testing the relationship between quinoa seed germination and constant temperatures (8–35 °C) showed a positive linear relationship between temperature and germination rate. The results suggested also that the germination base temperature was estimated to be constantly 3 °C, while germination optimal temperature showed variation within populations, so that 80% of the seeds in the population had germination optimal temperature values of 30–35 °C which is clearly in agreement with our results.

This study evaluated the effect of increased air temperature on growth, productivity, and associated traits of quinoa and addressed the gap in literature on the response of quinoa to heat stress, particularly under hot climate conditions such as

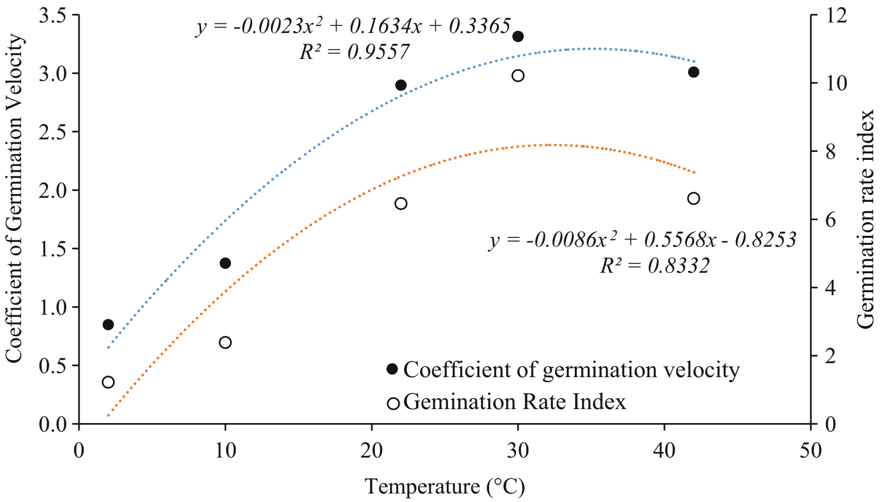

Fig. 7.12 Relationship between temperature, average coefficient of germination velocity, and germination rate index

UAE conditions. Increased air temperature had a negative impact on all morphological traits including plant architecture and leaf architecture. The negative impact of high temperature on the crop biomass of quinoa could be explained by the effect on either the crop cycle duration or crop growth rate (Lesjak and Calderini 2017). Very few are the studies reporting the impact of heat stress on quinoa growth and productivity. Hinojosa et al. (2016) reported that 68 quinoa genotypes produced seeds under the high-temperature treatment (max 40 °C). The remaining genotypes (44) did not produce seeds. This experiment concluded that the genotypes Baer, QQ74, Pison, and BGQ352 are potential heat-tolerant genotypes. Yang et al. (2016) tested quinoa under three irrigation levels and two temperatures: low temperature, the day/night climate chamber temperature was maintained at 18/8 °C, and 25/20 °C for high temperature throughout the treatment period. His finding indicates that quinoa height and biomass weight increased with increased temperature and decreased with increased water stress. In fact, a temperature equal to 25 °C is still an optimal temperature for quinoa growth and development.

Temperature is a primary factor affecting plant development. Higher temperatures are expected with climate change, and the potential for more extreme temperature events will impact plant growth and productivity. Pollination is one of the most sensitive phenological stages to temperature extremes across all species, and during this developmental stage, temperature extremes would greatly affect production (Hatfield and Prueger 2015). The flowering and yield results indicate a great effect of heat stress on reproductive stages causing a zero-seed production of all tested accessions under extreme heat stress, and this is was mainly explained by the pollen viability and sterility as well as reduction in flowers' number (Morrison and Stewart 2002).

Drought- and heat-induced reduction in photosynthetic capacity has been extensively reported in literature due to decreased stomatal conductance and damaged photosynthetic machinery (Silva et al. 2010; Wang et al. 2010). Similar to this, in the current study, stomatal conductance was significantly reduced under water and heat stress. It might be because both temperature and drought stress primarily caused injury to photochemical reaction site (Wise et al. 2004). It was shown in this study that stomatal conductance was more affected under water stress, and this is explained by the fact that plants when subjected to drought synthetize abscisic acid (ABA) which leads to increased ABA concentration in the leaves and therefore decreased stomatal conductance (Yang et al. 2016; Jacobsen et al. 2009).

7.5 Conclusion

Quinoa responses to heat and water stress under GCC region conditions are a research priority since this region is characterized by a harsh climate and scarce water resources. Therefore, quinoa as a drought-tolerant crop could be a practical solution to increase land and water productivity especially that quinoa becomes now an attractive food commodity in the GCC region in general and UAE in particular.

The finding of this research shows obviously that quinoa can be grown under high temperature up to 30 °C; however, few are the accessions that can produce seeds under temperature equal to 35 °C. Obtained data indicated that heat stress affected greatly most of growth and development parameters. Seed yield was greatly declined due to flowering inhibition and pollen sterility. The data set reported in this paper can be useful for breeders to determine the appropriate growing cycle of quinoa in the region or in other similar conditions. In the most of GCC countries, weather conditions are very suitable to grow quinoa from late October to late April; however, it is very important to avoid late sowing to escape from heat occurred during flowering which can affect seed production. According to climate conditions of UAE, a sowing date from late October to end of January will be suitable for quinoa.

References

Abugoch James LE (2009) Chapter 1 Quinoa (*Chenopodium quinoa* Willd.): composition, chemistry, nutritional, and functional properties. In: Steve LT (ed) Advances in food and nutrition research, vol 58. Academic, Amsterdam, pp 1–31. https://doi.org/10.1016/S1043-4526(09)58001-1

Barnabás B, Jäger K, Fehér A (2008) The effect of drought and heat stress on reproductive processes in cereals. Plant Cell Environ 31(1):11–38. https://doi.org/10.1111/j.1365-3040.2007.01727.x

Bazile D, Jacobsen SE, Verniau A (2016) The global expansion of quinoa: trends and limits. Front Plant Sci 7:622. https://doi.org/10.3389/fpls.2016.00622

Bertero HD (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

Bois JF, Winkel T, Lhomme JP, Raffaillac JP, Rocheteau A (2006) Response of some Andean cultivars of quinoa (*Chenopodium quinoa* Willd.) to temperature: effects on germination, phenology, growth and freezing. Eur J Agron 25(4):299–308. https://doi.org/10.1016/j.eja.2006.06.007

Bonifacio A (2005) Frost and hail tolerance in quinoa crop and traditional knowledge to handle those adverse factors. In: Jarvis D, Mar I, Sears L (eds) Enhancing the use of crop genetic diversity to manage abiotic stress in agricultural production systems, Budapest, Hungary, 2005. International Plant Genetic Resources Institute, Rome, Italy, pp 68–71

Chaves MM, Pereira JS, Maroco J, Rodrigues ML, Ricardo CPP, Osório ML, Carvalho I, Faria T, Pinheiro C (2002) How plants cope with water stress in the field? Photosynthesis and growth. Ann Bot 89(7):907–916

Choukr-allah R, Nanduri KR, Hirich A, Shahid M, Alshankiti A, Toderich K, Gill S, Butt KUR (2016) Quinoa for marginal environments: towards future food and nutritional security in MENA and Central Asia regions. Front Plant Sci 7(346):1–11. https://doi.org/10.3389/fpls.2016.00346

de Munter JS, Hu FB, Spiegelman D, Franz M, van Dam RM (2007) Whole grain, bran, and germ intake and risk of type 2 diabetes: a prospective cohort study and systematic review. PLoS Med 4(8):e261

Eisa S, Hussin S, Geissler N, Koyro HW (2012) Effect of NaCl salinity on water relations, photosynthesis and chemical composition of quinoa (*Chenopodium quinoa* Willd.) as a potential cash crop halophyte. Aust J Crop Sci 6(2):357–368

Farooq M, Bramley H, Palta JA, Siddique KH (2011) Heat stress in wheat during reproductive and grain-filling phases. Crit Rev Plant Sci 30(6):491–507

Fghire R, Wahbi S, Anaya F, Issa Ali O, Benlhabib O, Ragab R (2015) Response of quinoa to different water management strategies: field experiments and Saltmed model application results. Irrig Drain 64(1):29–40. https://doi.org/10.1002/ird.1895

Filali K, Hirich A, Ouafae B, Redouane C-A, Ragab R (2017) Yield and dry matter simulation using the Saltmed model for five quinoa (*Chenopodium Quinoa*) accessions under deficit irrigation in South Morocco. Irrig Drain 66:340. https://doi.org/10.1002/ird.2116

Geerts S, Raes D, Garcia M, Taboada C, Miranda R, Cusicanqui J, Mhizha T, Vacher J (2009) Modeling the potential for closing quinoa yield gaps under varying water availability in the Bolivian Altiplano. Agric Water Manag 96(11):1652–1658. https://doi.org/10.1016/j.agwat.2009.06.020

Geerts S, Raes D, Garcia M, Vacher J, Mamani R, Mendoza J, Huanca R, Morales B, Miranda R, Cusicanqui J, Taboada C (2008) Introducing deficit irrigation to stabilize yields of quinoa (*Chenopodium quinoa* Willd.). Eur J Agron 28(3):427–436

Gibson L, Paulsen G (1999) Yield components of wheat grown under high temperature stress during reproductive growth. Crop Sci 39(6):1841–1846

Giovannini C, Lucchesi S, Giachetti M (1990) Effects of heating on some chemical parameters related to soil fertility and plant growth. Soil Sci 149(6):344–350

Hasanuzzaman M, Nahar K, Alam MM, Roychowdhury R, Fujita M (2013) Physiological, biochemical, and molecular mechanisms of heat stress tolerance in plants. Int J Mol Sci 14 (5):9643–9684

Hatfield JL, Prueger JH (2015) Temperature extremes: effect on plant growth and development. Weather Clim Extrem 10(part a):4–10. https://doi.org/10.1016/j.wace.2015.08.001

Hinojosa L, Kumar N, Gill K, Murphy K (2016) High-throughput phenotyping to evaluate heat stress response in quinoa. Paper presented at the Annual Meeting of the American Society of Agronomy, Crop Science Society of America and Soil Science Society of America, At Phoenix - Arizona,

Hirich A (2013) Using deficit irrigation with treated wastewater to improve crop water productivity of sweet corn, chickpea, faba bean and quinoa. Revue Marocaine des Sciences Agronomiques et Vétérinaires 2(1):15–22

Hirich A, Choukr-Allah R, Jacobsen S-E (2013) The combined effect of deficit irrigation by treated wastewater and organic amendment on quinoa (*Chenopodium quinoa* Willd.) productivity. Desalin Water Treat 52(10–12):2208–2213. https://doi.org/10.1080/19443994.2013.777944

Hirich A, Choukr-Allah R, Jacobsen S-E, El Yousfi L, El Omari H (2012) Using deficit irrigation with treated wastewater in the production of quinoa (*Chenopodium quinoa* Willd.) in Morocco. Revista Científica UDO Agrícola 12(3):570–583

Hirich A, Choukr-Allah R, Jacobsen SE (2014a) Quinoa in Morocco – effect of sowing dates on development and yield. J Agron Crop Sci 200(5):371–377. https://doi.org/10.1111/jac.12071

Hirich A, Choukr-Allah R, Jelloul A, Jacobsen S-E (2014b) Quinoa (*Chenopodium quinoa* Willd.) seedling, water uptake and yield responses to irrigation water salinity. Acta Hortic 1054:145–152

Hirich A, Fatnassi H, Ragab R, Choukr-Allah R (2016) Prediction of climate change impact on corn grown in the south of Morocco using the Saltmed model. Irrig Drain 65(1):9–18. https://doi.org/10.1002/ird.2002

Hirich A, Jelloul A, Choukr-Allah R, Jacobsen SE (2014c) Saline water irrigation of quinoa and chickpea: seedling rate, stomatal conductance and yield responses. J Agron Crop Sci 200:378–389. https://doi.org/10.1111/jac.12072

IPCC (2014) Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland

Jacobsen S-E, Liu F, Jensen CR (2009) Does root-sourced ABA play a role for regulation of stomata under drought in quinoa (*Chenopodium quinoa* Willd.). Sci Hortic 122(2):281–287

Jacobsen S-E, Quispe H, Mujica A (2000) Quinoa: an alternative crop for saline soils in the Andes. CIP Program Report

Jacobsen S, Bach A (1998) The influence of temperature on seed germination rate in quinoa (*Chenopodium quinoa* Willd). Seed Sci Technol (Switzerland) 26 (2):515–523
Jacobsen SE, Monteros C, Christiansen JL, Bravo LA, Corcuera LJ, Mujica A (2005) Plant responses of quinoa (*Chenopodium quinoa* Willd.) to frost at various phenological stages. Eur J Agron 22(2):131–139. https://doi.org/10.1016/j.eja.2004.01.003
Jacobsen SE, Monteros C, Corcuera LJ, Bravo LA, Christiansen JL, Mujica A (2007) Frost resistance mechanisms in quinoa (*Chenopodium quinoa* Willd.). Eur J Agron 26(4):471–475. https://doi.org/10.1016/j.eja.2007.01.006
Jiang Y, Huang B (2000) Effects of drought or heat stress alone and in combination on Kentucky bluegrass. Crop Sci 40(5):1358–1362
Kader M (2005) A comparison of seed germination calculation formulae and the associated interpretation of resulting data. J Proc R Soc N S Wales 138:65–75
Kader M, Jutzi S (2004) Effects of thermal and salt treatments during imbibition on germination and seedling growth of sorghum at 42/19 C. J Agron Crop Sci 190(1):35–38
Kim H-J (2016) Opportunities and challenges of alternative specialty crops: the global picture. Hort Sci 51(11):1316–1319
Koyro H-W, Eisa S (2008) Effect of salinity on composition, viability and germination of seeds of *Chenopodium quinoa* Willd. Plant Soil 302(1):79–90. https://doi.org/10.1007/s11104-007-9457-4
Koyro H-W, Lieth H, Eisa SS (2008) Salt tolerance of *Chenopodium quinoa* Willd., grains of the Andes: influence of salinity on biomass production, yield, composition of reserves in the seeds, water and solute relations mangroves and halophytes: restoration and utilisation. In: Lieth H, Sucre MG, Herzog B (eds) Tasks for vegetation science 34, vol 43. Springer, Netherlands, pp 133–145. https://doi.org/10.1007/978-1-4020-6720-4_13
Lesjak J, Calderini DF (2017) Increased night temperature negatively affects grain yield, biomass and grain number in Chilean quinoa. Front Plant Sci 352:8
Morrison MJ, Stewart DW (2002) Heat stress during flowering in summer Brassica. Crop Sci 42 (3):797–803
Nsimba RY, Kikuzaki H, Konishi Y (2008) Antioxidant activity of various extracts and fractions of Chenopodium quinoa and Amaranthus spp. seeds. Food Chem 106(2):760–766
Panuccio MR, Jacobsen SE, Akhtar SS, Muscolo A (2014) Effect of saline water on seed germination and early seedling growth of the halophyte quinoa. AoB Plants 6:plu047. https://doi.org/10.1093/aobpla/plu047
Prasad P, Staggenborg S, Ristic Z (2008) Impacts of drought and/or heat stress on physiological, developmental, growth, and yield processes of crop plants. In: Ahuja LR (ed) Response of crops to limited water: Understanding and modeling water stress effects on plant growth processes, Advances in Agricultural Systems Modeling Series 1, vol Response of Crops. ASA-CSSA-SSSA, Madison, WI, pp 301–355
Radin JW (1984) Stomatal responses to water stress and to abscisic acid in phosphorus-deficient cotton plants. Plant Physiol 76(2):392–394
Razzaghi F, Ahmadi SH, Jacobsen SE, Jensen CR, Andersen MN (2012) Effects of salinity and soil–drying on radiation use efficiency, water productivity and yield of quinoa (*Chenopodium quinoa* Willd.). J Agron Crop Sci 198(3):173–184. https://doi.org/10.1111/j.1439-037X.2011.00496.x
Seif-Ennasr M, Zaaboul R, Hirich A, Caroletti GN, Bouchaou L, El Morjani ZEA, Beraaouz EH, McDonnell RA, Choukr-Allah R (2016) Climate change and adaptive water management measures in Chtouka Aït Baha region (Morocco). Sci Total Environ 573:862–875
Shabala S, Hariadi Y, Jacobsen SE (2013) Genotypic difference in salinity tolerance in quinoa is determined by differential control of xylem Na (+) loading and stomatal density. J Plant Physiol 170(10):906–914. https://doi.org/10.1016/j.jplph.2013.01.014
Silva EN, Ferreira-Silva SL, de Vasconcelos FA, Ribeiro RV, Viégas RA, Silveira JAG (2010) Photosynthetic changes and protective mechanisms against oxidative damage subjected to

isolated and combined drought and heat stresses in Jatropha curcas plants. J Plant Physiol 167 (14):1157–1164

Wang G, Li F, Zhang J, Zhao M, Hui Z, Wang W (2010) Overaccumulation of glycine betaine enhances tolerance of the photosynthetic apparatus to drought and heat stress in wheat. Photosynthetica 48(1):30–41

Wheeler T, Von Braun J (2013) Climate change impacts on global food security. Science 341 (6145):508–513

Winkel T, Lhomme JP, Laura JPN, Alcón CM, del Castillo C, Rocheteau A (2009) Assessing the protective effect of vertically heterogeneous canopies against radiative frost: the case of quinoa on the Andean Altiplano. Agric For Meteorol 149(10):1759–1768. https://doi.org/10.1016/j.agrformet.2009.06.005

Wise R, Olson A, Schrader S, Sharkey T (2004) Electron transport is the functional limitation of photosynthesis in field-grown pima cotton plants at high temperature. Plant Cell Environ 27 (6):717–724

Yang A, Akhtar S, Amjad M, Iqbal S, Jacobsen SE (2016) Growth and physiological responses of quinoa to drought and temperature stress. J Agron Crop Sci 202:445

Yazar A, Incekaya Ç, Sezen SM, Jacobsen S-E (2015) Saline water irrigation of quinoa (Chenopodium quinoa) under Mediterranean conditions. Crop Pasture Sci 66(10):993–1002

Zevallos V, Herencia L, Ciclitira P (2015) Quinoa, coeliac disease and gluten-free diet. In: Bazile D, Bertero H, Nieto C (eds) State of the art report on quinoa around the world in 2013. FAO, Rome

Chapter 8
Root and Shoot Relation of the Quinoa and Forage Plants in Salt-Affected Clay Soil

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Abstract Plant green biomass and morphology are closely related aspects of organ development; however, biomass accumulation patterns of agricultural crops are often complex and influenced by the growth environment. The objectives of this study were to evaluate (1) the effects of salinity and drought stress on the root mass (RM) to shoot mass (SM) ratio (RSR) of six agricultural crops (ICBA quinoa line Q3 compared with local maize, sorghum, amaranth, proso millet, and alfalfa) grown on the salt-affected (electrical conductivity [EC] = 6–12 dS m^{-1}) semi-arid clay soils, (2) the relationship between stem diameter (SD) and root biomass (RM) of plants, and (3) the impact of soil texture (loam and clay) on biomass accumulation of quinoa. At two fertilizer levels, three deficit irrigation regimes (0.4, 0.6, and 0.9 $\times$ *I*, where *I* is full irrigation) were applied to quinoa, and for the rest of the plants, only one irrigation regime (0.6 $\times$ *I*) was used.

The results revealed that (1) the combination of salinity and drought stress reduced SM and RM, resulting in a lower RSR (at harvest) by altering water deficit or fertilizer level. Quinoa had a greater allocation of biomass to roots and shoot (quinoa > maize > sorghum > amaranth > proso millet > alfalfa) and similar or lower RSR than other forages (quinoa = maize = sorghum = amaranth < proso millet < alfalfa) and could be categorized by a higher level of salt tolerance than other crops to grow and produce viable biomass and improve physical and chemical

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properties of soil. However, the harvest index of quinoa is less affected by treatments and was considerably lower than reported in the literature (e.g., grown in course textured and well-watered soils), showing that continuing relevant research is essential, (2) a unique relationship between RM on SD was established using a power function ($R^2 = 0.9$, $p < 0.001$) with the coefficient and exponent range of 0.03–0.1 and 1.5–2.1 respectively, showing that parameters of allometric relationships could be used to characterize the contributions of plants species and growing condition, and predict root biomass for carbon sequestration purposes, and (3) the RSR of quinoa planted in loamy soil was about two times higher than that grown in clay soil; the soil texture significantly changed the biomass allocation to shoot and roots, but slightly affected the exponent of the scaling relationship between SD and RM, suggesting that generally environmental factors controlled the biomass allocation to roots and leaves and ontogenetic drift dominated the biomass allocation to stems. The anticipated outcomes may allow understanding of the plant response to environmental incline, the selection of cultivars adapted to the most diverse abiotic stresses, and improving the productivity of economically essential quinoa or forages for agricultural sustainability.

Keywords Quinoa · Forage crops · Abiotic stress · Clay soils salinity · Allometry · Root to shoot ratio · Ontogenesis

8.1 Introduction

8.1.1 Problem of Salinity

Soil salinity is a global problem that affects approximately 40% (>610,000 ha) of the irrigated land in Azerbaijan. Most of the salt-affected and alkaline agricultural lands (electrical conductivity [EC] = 4–20 dS m^{-1}) is located in the central part of the Kur-Araz lowland, which is characterized by variable arid and semi-arid climate conditions and heavy clay soil texture, along with intense erosion and substantially degraded areas with low fertility and agricultural productivity. The average annual temperature and precipitation vary from 10 to 14 °C and 180 to 360 mm, respectively (<60–100 mm during May–August). The productivity of agricultural lands under such salinity and drought-stressed conditions or drylands might be aggravated by climate change and global warming due to (1) the sharp change in precipitation pattern and temperature; (2) a deficit of fresh irrigation water and the possibility of using low-quality effluent, irrational management, and irrigation with lower water and nutrient use efficiency; (3) inadequate functioning of the drainage system and secondary salinization and sodification; (4) incompatible agriculture and cropping patterns, such as limited on-farm management systems, application of modern water saving technology and practice, mono-cropping of wheat, corn and cotton, and rangeland overgrazing (Ismailov 2013; FAO 2016; Nurbekov et al. 2016). Sustainability of the agroecosystem in salt-affected marginal lands with scarce water resources could be preserved by integrating new soil management and conservation practices and cropping systems, improving crop rotation and nutrient management by introducing salt- and drought-tolerant crop varieties, and using organic and bio-fertilizers to access better soil and crop quality. Appropriate evaluation of non-traditional and traditional crops tolerant to abiotic and biotic stress, including high salinity (e.g., quinoa, sorghum, amaranth, proso millet, legumes, perennial grass, and bio-energy halophytes) may become an integral component of improving local food, crop-livestock feeding, farming production, and land rehabilitation systems (Rengasamy 2010; Hatfield 2013; Qadir et al. 2014; Choukr-Allah et al. 2016).

8.1.2 Abiotic Stresses

Plant growth and yield are negatively affected by abiotic stresses that influence various processes in soil-plant system, such as photosynthesis and respiration, ion uptake and translocation, carbohydrate and nutrient use. Drought stress (e.g., soil moisture below available level [pF = 2.7–4.2]), triggered by the decline in water content, negatively affects leaf water potential and cell enlargement and plant development (both elongation and expansion) and yield. Therefore, critical level of abiotic stress may result in the seizure of photosynthesis, metabolism, and ultimately plant death. Salinity (EC $>$ 2–4 dS m^{-1}) reduces plant growth and the quality and quantity of yields via the osmotic embarrassment of root water uptake, which influence cell division and expansion and plant stomatal conductance. High salinity elevate osmotic pressure of the soil solution and reduce water availability and thus normal intensity of water and nutrient uptake by plant roots, which leads to biological drought (Bartels and Sunkar 2005; Roy et al. 2014).

Plants can perceive abiotic stresses and elicit appropriate responses with modified metabolism, growth, and development. The available inclusive survey of the salt tolerance of crops and pasture species presents (Maas and Hoffman 1977), for each species, a threshold salinity (e.g., EC = 2–4 dS m^{-1} for most plants) below which there is no decrease in yield and then a linear reduction in yield with increasing salinity. However, the physiological responses of plants to salinity are often complex and multi-faceted and associated with other stresses (e.g., drought, nutrient deficit, low aeration, heavy metals, contamination, various temperatures, radiation, pathogens, texture, compaction), which makes research experiments difficult to design and interpret. The salinity tolerance mechanisms proposed by Munns and Tester (2008) include ion exclusion (the net exclusion of toxic ions from the shoot), tissue tolerance (the unconscious psychological defense mechanism of toxic ions in specific tissues, cells and sub-cellular organelles), and shoot ion-independent tolerance (the maintenance of growth and water uptake independent of the extent of Na accumulation in the shoot). Other physiological components may contribute to salinity tolerance, such as the leaf area, seed germination and early seedling growth, maintenance of plant water status and transpiration, harvest index, and root-shoot mass relationship (e.g., review paper by Acosta-Motos et al. (2017) and references cited therein).

8.1.3 Quinoa as a Salt- and Drought-Tolerant Crop

Quinoa (*Chenopodium quinoa*), as a crop tolerant to abiotic stresses (e.g., drought and salinity) and other adverse environmental factors (e.g., cold, pests and diseases, different photoperiods, and pH = 5–9), would be a useful model species for investigating morphological, physiological, and biomolecular mechanisms of salinity tolerance and salinity interaction with other environmental factors and microbiological features. This plant also represents a valuable resource for collection of the most suitable material and for breeding new varieties adapted to different soil and environmental conditions. Quinoa ecotypes display wide genetic variability and growing periods (100–160 days) and have been introduced into agricultural practice in more than 70 countries. Besides its use for human consumption, its seed and stover have other uses as livestock and poultry feed. It is a good source of protein and several minerals (Ca, Mg, Cu, Zn, and Fe), starch, lipids, amino acid composition, thiamine, folic acid, and vitamins (A, B2, E, and C) in comparison with other cereals. Several quinoa cultivars with various agroindustrial uses could be more competitive against other food, fodders, and forage products. Along with other forages (e.g., biodiversity), quinoa could be used as a crop in changing climate circumstances in which limited water resources and increasing soil salinization and water mineralization are the crucial causes of soil and crop loss (Bertero 2001; Soliz-Guerrero et al. 2002; Razzaghi et al. 2011a; Ruiz et al. 2014; Aurita-Silva et al. 2015; Biondi et al. 2015; Choukr-Allah et al. 2016).

A review of the salt tolerance of the world various quinoa accessions showed that increasing salinity considerably reduced quinoa plant growth, total seed yield, number of seeds, fresh and dry weight of seeds, height and biomass of some genotypes, while others were not considerably affected, or may even show an increase at a certain level of salinity. Not only species but also genotypes of the same species may differ considerably in their tolerance to abiotic stresses such as salinity, drought, or heat (Biondi et al. 2015). Salinity may have a different effect on seed germination, crop growth rate, and yield in various quinoa genotypes. Similar to halophytes, while some varieties of quinoa are able to survive very high levels of salinity (EC ~50 dS m^{-1}) in field condition and greenhouse tests (mostly in soil with course texture), its yield is usually high under conditions of moderate salinity (EC $\leq$10–20 dS m^{-1}). High osmotic tolerance for the period of germination may be a benefit in drought-affected and slightly saline soils, whereas tolerance to ion toxicity would be advantageous under greatly salinity conditions (Jacobsen et al. 2003; Gomez-Pando et al. 2010; Hariadi et al. 2011). The interaction of salinity with other associated environmental factors shows that if a plant is tolerant to water stress, it can also tolerate salt stress. Plants cope with drought stress by changing and modifying key physiological processes, such as photosynthesis, respiration, water uptake, and antioxidant and hormone metabolism. This is an essential aspect to use when selecting for a new variety, since in arid and semi-arid regions abiotic stresses (heat, water and salt) occur simultaneously (Hamed et al. 2013).

8.1.4 Forage Crops

To improve the potential of crops in salt-affected marginal environments, testing of new and high-yielding plants with high nutritional quality is essential. The physiological adaptability that allows forage crops (e.g., used as fodder for livestock), such as quinoa (*Chenopodium quinoa*), sorghum (*Sorghum bicolor*), maize (*Zea mays*), amaranth (*Amaranthus* spp.), proso millet (*Panicum miliaceum*), and alfalfa (*Medicago sativa*) to grow under harmful conditions symbolizes an important opportunity and offers huge prospective in the aspect of climate change challenges. One approach toward evaluating salinity tolerance is to compare various forage crops in terms of seed germination, growth, and yield under saline environments and to investigate the morphological and physiological mechanisms responsible for these variances. Extensive investigations will be necessary to evaluate the combined effect of drought and salinity at various stages of quinoa or forages growth, which is necessary for agricultural production in arid and semi-arid zones under various climate change scenarios (Gray and Brady 2016).

Quinoa and forage crops display various adaptive strategies to abiotic stresses, where response to drought involves changes in stem, leaf, and root growth. Mechanisms related to drought resistance of plants may include drought escape, tolerance, and avoidance. Similarly, their reactions and mechanisms for dealing with high salinity and low water accessibility can be related to salt adoption and stress avoidance and stress tolerance (Jacobsen et al. 2003; Adolf et al. 2013; Claeys and Inze 2013). Under field conditions, this combination of stresses may become complicated and may not show significant interaction between them on seed yield and harvest index, plant biomass, or water productivity. Plant physiology, root development, architecture, and morphology may differ widely because of many interrelating factors, such as plant phenology, abiotic stress intensity and duration, and soil properties and condition (Bolinder et al. 2002; Razzaghi et al. 2011a, b). Moreover, salinity, water, and nutrients are not evenly distributed in the agricultural fields of various climatic regions. Hence, the characteristics of root systems along with shoots are crucial for optimal use of the available resources. Roots play a crucial role in the establishment and performance of plants, although current studies on abiotic stress and plant selection are mainly focused on aboveground, shoot-related phenotypes, whereas most major drivers of the yield gap impact soil properties, directly influencing the root system (Fitter 2002; Gonzalez et al. 2009; Rengasamy 2010; Smith and De Smet 2012; Fageria 2013; Acosta-Motos et al. 2017).

8.1.5 Allometric Relationships

Plant species have diverse patterns for the transport of photosynthate and distribution to stems, leaves, and roots, which are influenced by plant ontogenetic drifts and environmental factors (Niklas and Enquist 2004). The ability of plants to adapt to the environment can affect plant organ mass fraction in annual plants and, hence, allometric relationships. Plants generally alter organ morphology rather than adjust allocation (Poorter et al. 2012a). Under agricultural management conditions using easily measurable plant parameters, such as the dry mass of plant organs at various vegetative stages, plant height, and stem diameter (SD) can provide data essential for estimating crops water and nutrient requirements, and carbon sequestration rates. The influence of forage genotype on plant morphology, as well as shoot, leaf, and root mass per plant allocable under saline and drought conditions, and allometric relationships may reflect its tolerance level, water and nutrient stress, and the contribution of soil texture or compaction (Niklas and Enquist 2004; Fageria et al. 2006; Xie et al. 2012; Song et al. 2015; Price and Munns 2016).

Allometric parameters such as root mass (RM), shoot mass (SM), and their ratio (RSR), the harvest index, vary over a broad range and depend on growing environments. Crop adaptation to soil conditions is dependent on root system development; thus, crop abiotic stress tolerance, survival, and capability are determined by root system development and architecture. However, the belowground part of a plant, the root system, is not valued enough largely due to the essential difficulty of accessing it for studies, seriously obstructing an objective analysis of allocation patterns in the field (Fitter 2002; Lux and Rost 2012; Fageria 2013). Counting available allometric relationships in crop models may improve their consistency, and this is vital when the models are used as a tool for crop management and validation in better farming. Knowledge of ontogenetic allometric relationships in agricultural plants could be an important approach to sustainable cropping (Reddy et al. 1998; Claeys and Inze 2013).

Shoot and root for growth and development is considered as interdependent. The roots depend on the shoot for carbohydrates, whereas the shoot depends on the root for water and nutrients. Thus, environmental abiotic stresses may increase the relative weights of roots compared to shoots. Nutrient- (e.g., fertilizer) and water-deficient plants may introduce more dry matter to roots than shoots (e.g., increase RSR), compared with unstressed ones, since water deficiency usually limits mostly shoots growth (Fageria and Moreira 2011; Lux and Rost 2012). The increase in RSR is a frequent reaction to salt stress. It is linked to features related to water stress, and osmotic effect, rather than a salinity one. Under salinity stress, a larger root mass can favor the retention of toxic ions in root cellular tissues and control their translocation to the plant organs, stem, and leaves, thus creating the characteristic mechanism of plant resistance. Low water quality associated with high salt content in the irrigation water or soil solution reduce plant maturing and leaf enlargement and alter the connection between the root and aerial parts. However, in ten experiments, the reducing effect of salinity on root growth of maize and soybean was mostly less severe than its effect on shoot growth (Shalhevet et al. 1995). Irrigation with mineralized water affected root system (e.g., mass, diameter, and density) and increased the RSR of horseradish and bottlebrushes at low-level of salinity ($EC = 4–6$ dS m^{-1}), whereas an increase in RSR of evergreen shrub and brush cherry was observed only during irrigation with water of higher salinity ($EC > 10$ dS m^{-1}). The latter plant species can improve the source to sink ratio for water and nutrients under such stress conditions (e.g., Acosta-Motos et al. 2017).

Morphological and physiological development of forages such as quinoa, sorghum, maize, amaranth, proso millet, and alfalfa as well as their growth performance and adaptation mechanisms to salinity and drought or their combination in arid and semi-arid zones have been generally investigated in numerous papers, where different irrigation, and nutrient management, soil, and climatic factors were employed (Shalhevet et al. 1995; Esechie et al. 2002; Bosque-Sanchez et al. 2003; Omami and Hammes 2006; Skinner and Comas 2010; Vasilakoglou et al. 2011; Islam et al. 2011; Zegada-Lizarazu et al. 2012; Castroluna et al. 2014). However, the contribution of salinity alone or associated with water and nutrient deficit on forages or quinoa, growth performance, biomass, and yield has shown inconsistent results associated with biological characteristics of the plant species and affecting management and environmental factors, including soil type (Hirich et al. 2012a, 2014a; Gonzalez et al. 2009; Gomez-Pando et al. 2010; Acosta-Motos et al. 2017).

Literature reviews have shown that, under salinity and drought stress, the available RSR for quinoa is very limited, particularly for field experiments in the fine-textured soils (Table 8.1). Moreover, shoot and root development (e.g., RM, SM) of the quinoa germplasm were widely varied at the mature stage, and abiotic stresses reduced or had no influence on both RSR and RM, but the relative impact of salinity was highly reliant on cultivars (Gomez-Pando et al. 2010). Most experiments were carried out in sandy soils or soilless or hydroponic material using smaller bags or pots (Table 8.1). Pot tests significantly reduce plant growth, which is caused by a reduction in photosynthesis per unit leaf area, rather than by changes in morphology or biomass allocation. A large plant mass per pot volume not only reduces the growth of roots and shoots but also seriously affects the relative differences between treatments (e.g., review by Poorter et al. 2012b). Soil texture significantly alters quinoa growth, and its water and nutrient uptake and, hence, the biomass and yield of plant. In contrast to salinity stress, the function of changes in root system development under water stress have been studied extensively, whereas the role of salinity, particularly in combination with water stress, on forage root system growth and mass is still unclear (Razzaghi et al. 2012; Noulas et al. 2015; Koevoets et al. 2016).

Little is known about the comparative responses (e.g., when experimental conditions are identical) of forages to the combination of salinity and water deficits and, hence, shoot and root performance in salt-affected clay soils with elevated alkalinity and crusting behavior. Moreover, there has been insufficient investigation of forages root growth interrelation to other plant organs (e.g., shoot, stem, leaves, and seeds) and soil texture and type of salinity. To our best knowledge, there is no available literature information (or there is insufficient literature data) regarding the relationship between root stem diameter (SD) and root biomass (RM) for forage or annual

Table 8.1 Root to shoot ratio of quinoa cultivars affected by abiotic stresses

Type	Treatments	Soil and test period	RSR	RM, g dry or fresh	Quinoa cultivars	References by year
Green house	Photoperiod	Hydroponic	0.059	0.12	CO407	Schlick and Bubenheim (1996)
	Irradiance	14 weeks	0.083	0.14	CO407	
			0.092	0.06	Real	
		7 weeks	0.076–0.112	0.28–0.58	QL3	
Pot	Salinity	Mixture	1.70–1.82		Real	Bosque-Sanches et al. (2000)
	Drought	4 weeks				
Pot	Drought	Loamy	0.048–0.084		Belen 2000	Geerts et al. (2006)
		22 weeks				
Pot	Drought	Sandy clay	0.21–0.22	0.060–0.084	Sajama	Gonzalez et al. (2009)
	Waterlogging					
Pot	Salinity	Substrate		2.0–43.0	Peruvian	Gomez-Pando et al. (2010)
					182 cultivars	
Pot	Salinity	Mixture	0.051–0.153	3.9–19.8 (f)	5206	Hariadi et al. (2011)
		10 weeks				
Plot	Drought	Clay loam	0.089		Amilda	Gonzalez et al. (2011)
		20 weeks	0.067		Chucapaca	
			0.091		CICA	
			0.059		Kamiri	
			0.048		Kancolla	
			0.070		Ratuqui	
			0.080		Robura	
			0.072		Sajama	
			0.073		Samaranti	
			0.080		Sayaña	
Plot	Deficit	Loam	0.100–0.127	31.9–43.3 (f)	DO708	Hirich et al. (2012a)
	Irrigation	14 weeks	0.108–0.153	33.9–56.4 (f)	QM1113	
		15 weeks	0.044–0.085	28.1–47.2 (f)	DO708	
Pot	Salinity	Hydroponic	0.143–0.170	2.5–16.0 (f)	Hualhuas	Eisa et al. (2012)
		9 weeks				
Plot	Deficit irrigation	Loam	0.110–0.140	2.30–4.90	DO708	Hirich et al. (2013)
	Amendments	14 weeks				

(continued)

Table 8.1 (continued)

Type	Treatments	Soil and test period	RSR	RM, g dry or fresh	Quinoa cultivars	References by year
Plot	Deficit irrigation	Loam	0.059–0.084	9.60–15.10	DO708	Hirich et al. (2014c)
		14 weeks	0.094–0.122	7.06–14.97	DO708	
			0.087–0.102	7.35–10.08	QM1113	
Plot	Deficit irrigation	Loam	0.059–0.096	9.54–16.02	DO708	Lavini et al. (2014)
		14 weeks				
Pot	Drought	Compost	0.11–0.13	1.23–1.27	KVL52	Stikic et al. (2015)
		6 weeks				
Pot	Salinity	Mixture	0.26–0.50	1.3–6.5	R49	Ruiz et al. (2016)
			0.15–0.20	0.6–0.9	V1–1	
			0.10–0.35	0.9–3.7	Villarrica	
Plot	Salinity	Clay	0.057–0.071	8.7–21.6	ICBA-Q3	Mamedov et al. (2016)
	Deficit irrigation	Loam	0.09–0.29	1.4–18.1		
		18 weeks				

crops (e.g., indirect prediction of root biomass and hence carbon input) in general. A deeper understanding of these issues at the soil-plant interaction would be beneficial for further improving salinity and drought resistance, water and nutrient use efficiency, and soil quality and productivity of potential forage crops under resource-limited environments, as well as taking appropriate action to prevent the problem that climate change may cause (Rengasamy 2010; Fageria and Moreira 2011; Acosta-Motos et al. 2017).

The objective of the study was to investigate (1) the effect of abiotic stress (e.g., salinity, water) on root mass (RM), shoot mass (SM), and the root to shoot mass ratio (RSR) of six forage and grain crops (quinoa, amaranth, sorghum, maize, proso millet, and alfalfa) in the semi-arid, salt-affected clay soils of the Central Kur-Araz lowland of Azerbaijan; (2) the allometric relationship between RM and SD for the plants; and (3) the contribution of soil type (texture) to quinoa plant ontogeny and biomass allocation.

8.2 Materials and Methods

As a part of multidisciplinary team since 2014, the Institute of Botany, ANAS, in collaboration with the International Center for Biosaline Agriculture (ICBA, Dubai, UAE), has been studying the growth performance and yields of large varieties and improved lines of forage and dual-purpose crops, including quinoa, in the saline environments of the Kur-Araz lowland. Evaluation of their potential suitability for a sustainable agroecosystem was also conducted. This paper will concentrate more on quinoa line (ICBA-Q3), which was first planted in the area in 2016, whereas local forages have been studied broadly.

8.2.1 Location and Soil

The field trials in 2016 were conducted in two cultivated locations with a saline clay and low-saline loam soil type. The experiments in salt-affected clay soils were carried out at the Kurdemir Experimental Station (~ 130 ha) of the Institute of Botany, ANAS, located in the middle part of the Kur-Aras lowland, on the right side of the Baku-Tbilisi highway (Fig. 8.1). Field work in loam soil with low salinity was conducted in the experimental station of the Botanical Garden, ANAS, located in the territory of the Institute. Soil sampling using the regular scheme showed that, due to the natural and previous cultivation history, the distribution of soil salinity of the clay soil was highly heterogeneous (EC $=$ 2–14 dS m^{-1}) in the upper layer (0–30 cm), but mostly characterized by moderate salinity and increased by soil depth. Groundwater with mineralization of 6–15 g l^{-1} was positioned 1.5–2.1 m from the soil surface. In a 1-ha territory of the experimental station after seed bed preparation, in situ field survey using the regular scheme was conducted (EC-probe, Eijkelkamp), and a precise soil salinity map with three levels of salinity (EC <4,

a) b) c)

Fig. 8.1 (**a**) Location of the field experimental station, Institute of Botany, ANAS (central part of the Kur-Araz lowland), (**b**) view of field before (March, 2015) the experiment (*Alhagi Maurorum*, Medik grown in salt-affected and crusted clay soil), and (**c**) during the cultivation of forages (May, 2016)

4–8, and 8–12 dS m^{-1}) was created and the marked areas with the same salinity range were fenced (0.4 ha).

A part of the surveyed area with moderate salinity (EC = 8–12 dS m^{-1}) was used for a deficit irrigation experimental study at two fertilizer level (plot size 2 × 3 m^2), since salinity in the territory of the Kur-Araz lowland mostly varied within this range (EC = 2–12 dS m^{-1}). Another part of the area was used to study plant performance in large plots (20 × 30 m^2) under the same irrigation rate and without fertilizer (Table 8.2). Large plots, with higher soil condition and management heterogeneity than small plots (e.g., traditional management), were used for stem thickness and root biomass measurements on randomly selected plants (24–80 plants) of various heights (70–180 cm). The cultivated layer of the clay and loam soils was characterized with a high carbonate level, moderately alkalinity, low organic matter and nutrient content, and low aggregate and structure stability (Table 8.2). Soils have a high bulk density (1.38 and 1.43 g cm^{-1}), and clay soil has crusting and high swelling potential due to considerable montmorillonitic clay mineralogy and variable elevated alkalinity (Fig. 8.1).

8.2.2 Experiments

Two sets of experiments in fields containing (1) clay soil and (2) loam soil were conducted with three replicates to evaluate plant growth, modification of plant organ morphology, and soil and plant quality (Table 8.2). In clay soil plots, an effect of moderate soil salinity and water stress and nutrient deficit on the growth of quinoa (ICBA-Q3) was studied using three deficit irrigation (fresh water) regimes (0.9, 0.6 and 0.4 × *I*, where *I* is full irrigation), whereas various local germplasms of forage crops (amaranth, sorghum, maize, proso millet, and alfalfa) were treated with only one (06 × *I*) irrigation rate, taking into consideration that the amount of available local water resources may, at most, allow irrigating forages with the 0.9 × *I* level (e.g. tentatively) and that local farmers usually use around (0.6–0.7 × *I*). For 0.6 and 0.9 × *I* treatments, 0.5 × *I* was applied during the vegetative growth stage (e.g. Hirich et al. 2012a, 2013), and 0.6 × *I* or 0.9 × *I* for the rest of period, whereas a 0.4 × *I* rate was applied during all irrigation periods. In small plots, all crops were treated with two levels of mineral fertilizer (control: NPK = 0; test: N150P50K50 kg ha^{-1}; fertilizers: NH_4NO_3, P_2O_5, KCl). Dry manure (5 t ha^{-1}) was applied to mitigate soil crusting and slightly improve soil nutrient and water holding capacity. In large plots (loam and clay) only a (0.6 × *I*) irrigation regime (no fertilizer) was applied (Table 8.3).

Sowing was conducted at the end of April 2016. One month before sowing, the field was plowed to a depth of 0.3 m, and then seedbed preparation was carried out prior to sowing with the disc-rotary harrowing method. The distance between rows was 50 cm and between crop seeds was 20 cm. Row and inter-row weed control during the growing cycle was done by hand cultivation. Fertilizer rate (NPK = 0 or N120P40K40 kg ha^{-1}) and microelements (4–12 g ha^{-1}) were applied as

Table 8.2 Selected properties of soil

Soil	Particles, %		CEC ($cmol_c\ kg^{-1}$)	pH (1:2)	EC ($dS\ m^{-1}$)	OM	WSA	FC	WP	N	P	K
	Clay	Sand				(%)					(ppm)	
Haplic	56	16	46.8	8.4	8.7	1.4	50.4	28.2	19.1	0.11	4.3	464
Calcisols	18	34	12.1	8.2	3.2	1.2	20.4	18.7	9.4	0.10	3.4	325

CEC cation exchange capacity, *OM* organic matter, *EC* electrical conductivity, *WSA* wet aggregate stability, *FC* field capacity, *WP* wilting point, N, P, and K, available nutrients

Table 8.3 Treatment experimental setup

Set	To study	Plot (m^2)	Soil	Plant	Irrigation	Fertilizer (kg ha^{-1})
1	RSR	2 × 3	Clay	Quinoa	0.4, 0.6, 0.9 × *I*	NPK = 0, N150P50K50
	RSR	2 × 3	Clay	5 Forages	0.6 × *I*	NPK = 0, N150P50K50
	RM & SD	20 × 30	Clay	All crops	0.6 × *I*	NPK = 0
2	RSR	20 × 30	Loam	Quinoa	0.6 × *I*	NPK = 0
	RM & SD					

I full irrigation

recommended, taking into consideration the influence of pH on nutrient availability. The total amount of phosphorus and potassium was applied at sowing. The amount of nitrogen was divided and supplied at sowing and again during vegetative growth before flowering. Furrow irrigations with 200–600 mm rates (total rain + irrigation water depth ~ 2000–4000 mm) were conducted in accordance with soil moisture content measured using a sensor (ES-5, Decagon Devices) and rain pattern approximately every 2–4 weeks.

The field trial design and observation, crop growth performance and parameters, and soil and plant analysis were carried out according to the developed guidelines (Klute 1986; Page et al. 1986; Estefan et al. 2013). During vegetation growth, *measurements* at various *phenological stages of crops* (emergence, vegetative growth, flowering, grain filling, and maturation) were studied for all plants, randomly taken from each plot. Conventional collapsible cylindrical type soil cores (diameter 20–30 cm, depth 50 cm) and shovels were used to collect soil-roots samples, and then root separation was performed carefully by hand and washing over a sieve using an elutriation system (e.g., Benjamin and Nielsen 2004). Plant SD was taken using a digital caliper (Neiko 01407A). Leaf area was obtained using an area integrator (LI-3100, Licor). Harvest was performed at the end of August 2016. Plant height, number of stems and leaves, leaf area, and SD were evaluated, and dry biomass (SM and RM) were determined by forced air oven drying at 65 °C. Root, shoot, grain, and soil samples were used for appropriate plant, soil, and/or image analysis. Image analysis was used to determine various root morphological parameters and root architecture (WinRHIZO, Regent Instruments Inc.).

8.2.3 Statistical Analysis

The analysis of variance procedure was performed to compare the effects of treatments (or their interaction) on vegetative and yield parameters. Treatment mean comparisons were made by employing the Tukey HSD test using a significance level of 0.05 (SAS Institute 1995). Allometry (relationships) was used to study the relative growth of crop parts and evaluate their structural development (e.g., Poorter et al. 2012a).

8.3 Results and Discussion

8.3.1 Quinoa Performance in Clay Soil

Climatic characteristics of the trial site were typical of a semi-arid area of the country. Over the same period, maximum air temperatures were higher than the long-term means, while the lowest temperatures were comparable (Mamedov et al. 2016). Potential evapotranspiration was generally higher than the long-term mean value by about 0.6–1.0 mm during the summer period. During May–August ~54 mm of rainfall (at the middle of May and beginning of July) was recorded, which notably influenced the vegetative growth phase and yield of plants. Laboratory pot (200 ml) and field seed germination (usually lower than the former due to the impact of a combination of stress factors) revealed that quinoa displayed average germination rates of 58 and 40%, respectively, during a 10-day period. In the field, the crop stand density was 18 plants per square meter. Quinoa started and performed relatively well during the early stage (within a month) of the plant growth and during the blossoming and grain formation period, compared with other forage crops. This genotype (ICBA-Q3) grew to 8–20, 65–138, and 86–165 cm height with 1, 2, and 3 months, respectively. Under the same salinity, deficit irrigation (e.g., drought) significantly reduced plant height, dry mass, and yield. Meanwhile 0.6–0.9 × *I* treatment with similar harvest indexes has positive outcomes for both fertilizer rates (Table 8.4).

A biological feature of quinoa was characterized by its slow growth during the initial growth period after germination. The duration of vegetation was 110–114 day, the starting to 50% and ending of flowering time were 44–48 and 56–60 days, and the duration from half to full flowering was 20–26 days. The number of quinoa shoot branches and the size of the panicle are important features of the plants and may evaluate their biological stability and better harvest. Quinoa had more than 14 branches (14–24), with panicle weight 12–16 g plant, and length 12–18 cm and 40–48 cm, respectively (Mamedov et al. 2016).

Table 8.4 Vegetative and yield parameters of quinoa (ICBA-Q3) as affected by drought in salt-affected clay soil

Treatments	Stem diameter, SD (mm)	Plant height (cm)	Shoot dry matter, SM (g)	Root dry matter, RM (g)	Root to shoot ratio RSR	Green yield (g m^2)	Harvest index
C—0.9 × *I*	19.4 ab	160 a	289 a	18.1 b	0.063 b	214 b	0.14 ab
C—0.6 × *I*	17.3 c	98 d	221 c	13.9 c	0.063 b	177 c	0.15 a
C—0.4 × *I*	11.1 d	86 e	178 d	8.7 d	0.049 d	123 e	0.13 ab
F—0.9 × *I*	22.1 a	165 a	303 a	21.6 a	0.071 a	242 a	0.15 a
F—0.6 × *I*	18.4 bc	123 b	247 b	16.9 b	0.068 ab	203 b	0.15 a
F—0.4 × *I*	13.3 e	108 cd	208 c	11.8 c	0.057 c	140 d	0.12 b

Columns labeled with the same letter are not significantly different at the $p < 0.05$ level
C Control, *F* fertilizer, *I* irrigation

Generally, higher values for plant height and basal stem thickness (e.g., SD) resulted in higher root and aboveground (shoot) dry biomass and yield (Table 8.4). Quinoa performance improvement (09 × *I* or 0.6 × *I* v. 0.4 × *I*) was because of the low bareness of the panicles that contributed to a higher number of seeds. The vegetative growth at 0.4 × *I* with higher combined salinity and drought stress led to notably lower yield or harvest index and RM values in both treatments (Table 8.4). Fertilizer application generally had a positive effect on shoot and root performance, positively affected RM, and slightly decreased RSR, because besides biomass allocation to shoots also root growth (and biomass) to deeper layers was restrained by higher soil salinity and texture and lower aeration. The 0.6 × *I* deficit irrigation had positive effects on harvest index and RSR, but decreased plant height and grain yield, yet had much better plant performance than seen with the 0.4 × *I* treatment (Table 8.4). In this semi-arid area, salinity is not uniform down the soil profile and usually increases by depth. March–May is typically a rainy period in the studied territory. In April, when a crop is sown, salinity is usually lower at the surface and greater at depth, and this tendency may become stronger after some leaching of the salt from the upper 5–10 cm layer. Seeds, therefore, germinate and grow in relatively low salinity, and root systems reach relatively higher salinity later. During the growing period, depending on the irrigation rate, evapotranspiration increases soil salinity in the upper layer and affects both proportion of root system modules and rooting depth and soil structure and water use performance caused by a saline gradient and water content (e.g., Rengasamy 2010; Galvan-Ampudia and Testerink 2011).

In addition to soil salinity and irrigation water deficit, crop development and biomass, and green yield were also considerably linked to the late seedling, notable precipitation just after germination, which probably caused low aeration conditions in swelling and crusting clay soil (Karyotis et al. 2003) and affected seed formation and size during grain maturation, harvest index, and yield, which was twice lower than the same quinoa grown in sandy or loam soils, although it was at levels comparable to those found in the literature (e.g., Gomez-Pando et al. 2010; Choukr-Allah et al. 2016). Also, this wet period was followed by a summer season where no notable rainfall was recorded. Literature studies at two contrasting location (e.g., arid and sub-humid) also revealed that, due to the climate parameters (e.g., temperature, photoperiod and solar radiation) and biotic factors, early and late quinoa sowing dates (2–4 weeks difference) show significant differences for plant height and length of panicle, whereas yield for the earlier sowing might be significantly higher (>1.2–2.0 times) than for the later due to the higher dry matter of the panicle that had a greater mean seed weight and, hence, harvest index (Pulvento et al. 2010; Hirich et al. 2014b).

Quinoa is more likely highly tolerant to soil salinity than water deficit (Table 8.4) and does not require preliminary fine leaching work before planting compared with traditional crops. Biomass and yield reduction under combined salinity and drought stress in heavy clay soils could be related to (1) an increase in stomatal resistance of quinoa when deficit irrigation is used and (2) a decrease in transpiration rate (e.g., low supply of photosynthate in the plant) and, hence, impaired photosynthetic capacity (Eisa et al. 2012; Yazar et al. 2015). Results were in line with the works of other authors (e.g., effect of soil or irrigation water salinity, plant growth stage and water deficit, fertilizer rate, sowing period, soil type, salinity type) conducted in the Mediterranean region (Hirich et al. 2012b; Hirich 2013; Lavini et al. 2014; Yazar et al. 2015; Wu et al. 2016b). In Morocco, sand pot experiments showed that increasing the salinity of the irrigation water (EC = 1–30 dS m^{-1}) significantly reduced the seedling rate and height, dry biomass, seed yield, root volume, and leaf cations concentration but increased harvest index and crop water productivity of quinoa; consequently, the salinity threshold was estimated as 8 dS m^{-1} for quinoa (Hirich et al. 2014c). In other experiments of the authors, the contribution of rainfed conditions and deficit irrigation (0, 0.25, 0.5, 0.75, and 1.0 × *I*) with treated waste water at various stages of plant stages (e.g., vegetative growth, flowering, grain filling) significantly reduced yield (30–50%) but increased crop water productivity and root weight of two line of quinoa in comparison with the full irrigation (Hirich et al. 2012a).

In an arid region of Turkey, Yazar et al. (2015) studied the contributions of fresh and saline water (EC = 10–40 dS m^{-1}) and deficit irrigation (0.6–1.0 × *I*) combinations to quinoa performance and yield in clay soil. The authors stressed that a combination of salinity and drought stress significantly altered the leaf area index, biomass and grain yield (14–32%). Since salinity stress alone did not considerably reduce plant yield, they defined quinoa was as a salt-tolerant crop. Moderate-deficit irrigation increased water use efficiency and quinoa yield, although soil salinity increased (up to 12 dS m^{-1}) in the upper cultivated layer, since less water was available for leaching the salts added by irrigation or groundwater evaporation (Yazar et al. 2015). Results from central Greece field experiments revealed that quinoa has a yield potential even on degraded soils, where under saline and sodic soil conditions, seed yield of quinoa grown in clay loam soil was reduced up to 50% relative to clay soil in the neutral pH range (Karyotis et al. 2003). The authors concluded that a wide range of soil types could be considered appropriate for quinoa production, but topsoil crusting, and drying can limit germination potential; hence, clay soils may be used for quinoa cultivation under proper and irrigation and fertilization managements (Karyotis et al. 2003). In contrast to the abovementioned studies, in sub-humid Southern Italy, where fresh and saline water (EC = 22 dS m^{-1}) and deficit irrigation (0.25, 0.5, and 1.0 × *I*) in clay loam soil were applied, quinoa (Titicaca), through stomatal responses and osmotic adjustments, could maintain a leaf turgor favorable for plant growth, and consequently saline and water stress did not caused considerable yield or yield quality reductions (Pulvento et al. 2012; Cocozza et al. 2013). Early spring could be used as the principal period for seed sowing in this semi-arid region, since immature plants have sufficient time for establishment and root development before the hot and dry summer season starts. In the end, positive results in reclamation of degraded and salt-affected marginal lands by using quinoa germplasm (e.g., analogous to sorghum) have been shown in many countries and may work in this semi-arid region with annual rainfall <200–400 mm (e.g., Hamed et al. 2013; Choukr-Allah et al. 2016).

8.3.2 *Plant Root System Development and Soil Structure*

Under abiotic stresses, plants roots have shown various adaptive capacities, the magnitude of which are most likely dependent predominantly on plant sensitivity to salinity or drought, which is associated with soil texture. In the main to the end of vegetation for all crops, most of the root mass (>90%) was concentrated within the upper 30 cm of soil thickness and was negatively affected by the combination of salinity and water stress (Mamedov et al. 2016). Plants, (1) in addition to modifying of the root system during salt stress, also reduced growth expansion in the vertical direction (e.g., gravitropism) of clay soil, (2) the number of nodal and lateral roots transmit growth past regions of higher salinity in deeper layers, and (3) under limited irrigation, increased biomass allocation caused by a higher amount of nodal and lateral roots and notable root hair formation, as well as regulation of the amount of crown roots. For instance, under moderate irrigation ($0.6 \times I$) in comparison with the control, a considerable shift from main root to lateral root growth and increase of root hairs were observed in amaranth root systems treated with fertilizer (e.g., P), whereas the depth of rooting between treatments was still comparable (Fig. 8.2).

Through balanced exploration of the soil for fertilizer, plants develop a shallow root system; therefore, root plasticity is important under low fertilizer and water conditions. Under water and nutrient stress, reaching deeper soils depths requires a

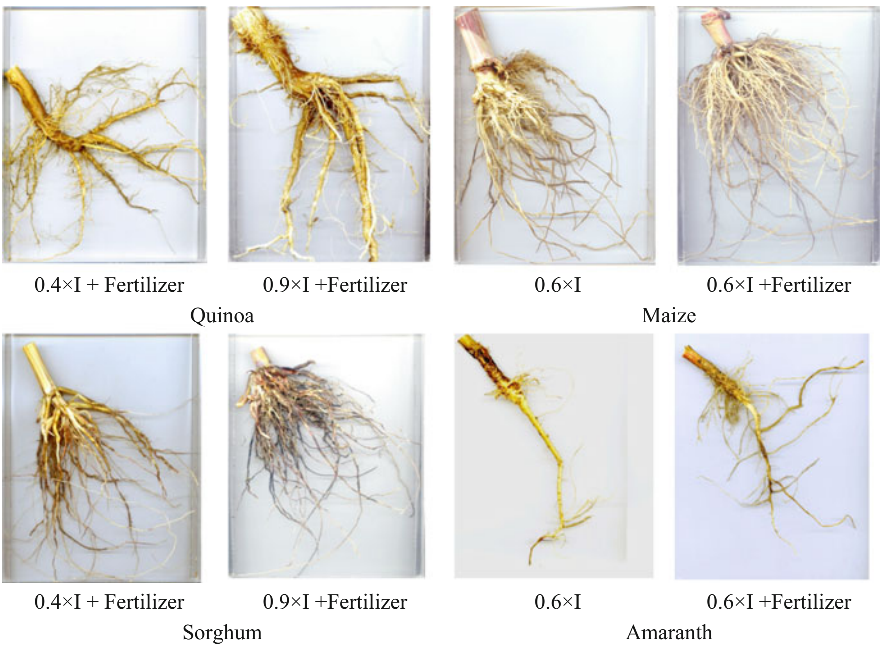


Fig. 8.2 Examples of images (A4 format) of roots of plants affected by deficit irrigation and fertilizer application: quinoa and maize, sorghum, and amaranth

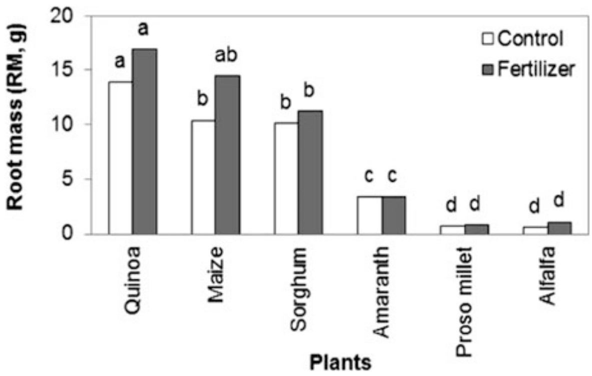


Fig. 8.3 Root mass (RM) of plants at the end of vegetation. Bars labeled with same letter are not significantly different at the $p < 0.05$ level

shift in allocation from lateral to axile roots. Other elements of plant roots (e.g. lateral, seminal, and crown) may demonstrate various growth patterns affecting axile growth in the direction of gravity. Root foraging capacity depends on root system architecture and ontogeny (e.g., Alvarez-Flores et al. 2014). In quinoa, positive gravitropism adjusts the root downward and enables penetration of soil with high salinity. The quinoa root system develops from a tap root to form a highly branched (Fig. 8.2) system that makes quinoa plants more resistant to abiotic stresses than other plants and reduces antagonism among roots of the same crop, as well as among roots of adjoining crops. This improves the use of soil, water and nutrient resources (Fitter 2002; Fageria and Moreira 2011), resulting in massive and higher RM than other forages (Figs. 8.2 and 8.3). Salinity and drought responses show overlap since they are caused by osmotic stress. However, main root growth is inhibited during salt stress, while it could be endorsed during water stress but could also be repressed if the underlying soil layer has high salinity and penetration resistance. Moreover, there is an apparent difference between the effects of salt on primary and lateral root growth. The quantification of root architecture with respect to salinity tolerance is still ambiguous, and little is known about root development of crops during salinity or combined salt and water stress. Future research studying the differences between these stresses associated with nutrient availability is important (Galvan-Ampudia and Testerink 2011; Koevoets et al. 2016; Wu et al. 2016a).

The tested plants produced a viable biomass on marginal crusting clay soil and generally improved its physical and chemical properties, which in turn caused an increase in the agronomic fertility of the cultivated land. The aggregate and structure stability, cation exchange capacity (CEC), and OM (e.g., based on organic carbon), of samples taken at the end of vegetation, was considerably higher in the cultivated root zone than in control bare soil (Table 8.5). Aggregate stability usually increases during the period of active root growth, peaks when root systems were at their top, and subsequently decreases when the root system declines. Root tips produce an insoluble lubricating gel that helps the root penetrate small pores, provides the root tip protection against drying, helps gather nutrients, and binds soil particles together into aggregates that allow for better soil aeration and water percolation (Table 8.5). Moreover, in addition to root biomass, rhizodeposit in the form of exudates,

Table 8.5 Cultivation effect of on selected soil properties

Treatments	CEC ($cmol_c kg^{-1}$)	OM (%)	WSA (%)	AW (%)	N (%)	P (ppm)	K (ppm)	pH	EC ($dS\ m^{-1)}$)
Control	43.5	1.2	51.7	8.2	0.08	2.0	431.3	8.7	7.55
Quinoa	55.4	1.6	67.2	12.5	0.14	5.1	594.0	8.2	5.66
Amaranth	50.0	1.8	67.2	10.8	0.14	11.7	504.3	8.2	5.02
Sorghum	53.5	1.7	66.3	10.9	0.13	7.4	574.2	8.6	5.54
Maize	52.0	1.6	71.0	11.5	0.15	5.0	543.0	8.6	6.28
Proso millet	50.5	1.6	64.3	9.1	0.16	15.1	610.4	8.3	5.94
Alfalfa	50.1	1.8	73.4	11.4	0.11	8.2	518.6	8.4	6.36
Significance	*	*	*	*	ns	*	*	*	ns

WAS water aggregate stability, *AW* available water, *OM* organic matter, *CEC* cation exchange capacity, *EC* electrical conductivity

*, the difference between the values from control and plant plots is significant at the $p < 0.05$ level

ns not significant

secretions, cap cells, lysates, and mucilages can also form important sources of carbon for enriching soil organic carbon and improving soil structure (Six et al. 2004).

The root systems developed by quinoa and forages may play a dominant role in the soil carbon cycle and may have relatively greater influence on soil organic matter than the aboveground plant biomass and alter soil salinity; water retention capacity and hydraulic conductivity; soil aggregate and structure stability; infiltration; and resistance against water or wind erosion. Root traits are important drivers of ecosystem processes and services in soil quality and conservation and should be included in sustainable agroecosystem management. For strategy purposes, understanding and quantitatively linking easily measurable plant morphological parameters of the root system, as well as the contribution of soil type on root system parameters to soil and crop model components, will be crucial (Daynes et al. 2013; Roumet et al. 2016; Hudek et al. 2017; Faucon et al. 2017).

8.3.3 Allometric Relationship: RSR of the Crops

Crop yield is driven by the combination of climate, soil, management, and genetics. The studied forage plant species have diverse patterns for transportation of photosynthate and distribution to shoot and root, which are influenced by ontogeny and environmental factors (Poorter et al. 2012a). Generally, in investigated semi-arid, salt-affected clay soil, the RSR of the plants increased as their RM decreased (Figs. 8.2 and 8.3). In clay soil, quinoa had a greater allocation of biomass to roots and shoot (quinoa > maize > sorghum > amaranthus > proso millet > alfalfa) and a similar or lower RSR (Fig. 8.4) than other forages (quinoa = maize = sorghum = amaranthus < proso millet < alfalfa). Fertilizer application positively affected both RM and SM and decreased RSR (Figs. 8.3 and 8.4). It appears that

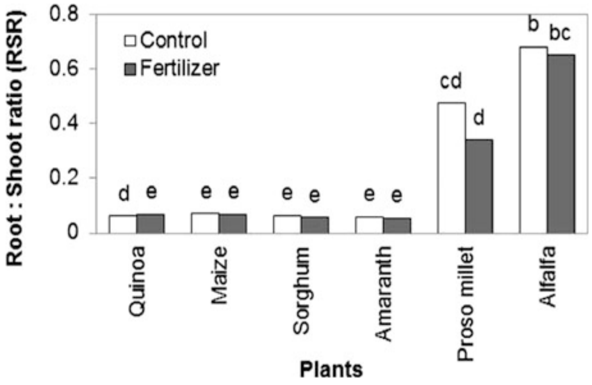


Fig. 8.4 Root to shoot ratio (RSR) of plants at the end of vegetation. Bars labeled with same letter are not significantly different at the $p < 0.05$ level

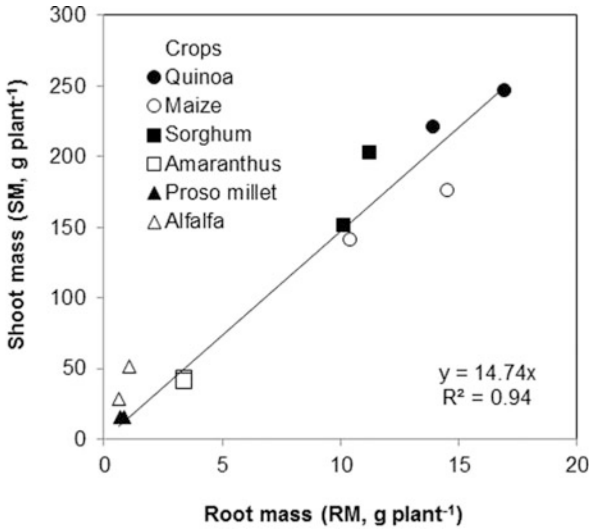
water deficit at early quinoa growth stages may stimulate root development, and improve water and nutrient uptake, and biomass production. Hence, well-organized deficit irrigation during plant establishment can mitigate water stress and stabilized quinoa yields (Choukr-Allah et al. 2016).

Relatively high phenotypic flexibility of quinoa works as a drought avoidance mechanism at moderate water deficit. As a result, the RSR and harvest index for $0.6 \times I$ and $0.9 \times I$ irrigations had similar or much higher values than for $0.4 \times I$ (Table 8.4). Moreover, cultivation of quinoa could be improved by fertilizer management practices, and N can ameliorate the negative effect of moderate water deficit, since N has an effect on the physiology of the crop, enhancing the tolerance to drought events. When nutrient is supplied to leaves from the roots, photosynthesis remains high during maturation, which secures the supply of carbohydrates to the roots (e.g., Geerts et al. 2008; Razzaghi et al. 2012; Hirich et al. 2012a; Alandia et al. 2016).

Throughout soil drying when stomata are closed, converting oxalic acid to carbon dioxide for photosynthesis permits higher water use efficiency in many plants. During drought, quinoa plants present a sensitive stomatal closure, by which the plants can maintain leaf water potential and photosynthesis rate, resulting in an increase in water use efficiency. Under water-deficit condition, chemical signaling from the root system plays an essential role in maintaining stomatal conductance. Root-related abscisic acid regulation indicates that the stress tolerance process also depends upon hydraulic control over a change in turgor and other chemical affluences to aid readability (Jacobsen et al. 2009).

Under high salinity, transpiration and gas exchange may considerable decrease in quinoa cultivars. Plant, subjected to various combination of drought and salt stress, increased abscisic acid concentration in shoot and root to adjust stomatal conductance (Bosque-Sanchez et al. 2003; Jacobsen et al. 2009; Hariadi et al. 2011; Razzaghi et al. 2011b). Decreases in the RSR of plants show that shoots have a greater significance for photosynthate gathering than roots. Consequently, if RSR increases with time, roots have favored consumption of photosynthates under the current plant growing environments. Changes in root biomass, and its water and

Fig. 8.5 Relationship between root and shoot biomass of plants in clay soil (0.6 × *I* and two fertilizer levels)



nutrient uptake capability, influencing plant biomass, yield, and seed quality. In shoots high maintenance of photoassimilate can improve the photosynthetic leaf area of the plant (Jacobsen et al. 2009; Fageria et al. 2006; Munns and Gilliham 2015; Acosta-Motos et al. 2017). Plant roots could be most vulnerable to salt stress, than shoots; however, they are more vigorous, and their development is less affected by salinity, than shoots (Munns 2002). Interestingly, under deficit (0.6 × *I*) irrigation, in comparison with other plants, quinoa had one of lowest RSRs, while having highest RM and SM for both fertilizer rates, showing its better adaptability to combined stresses than other crops (Figs. 8.3, 8.4, and 8.5).

In arid and semi-arid region climates, clay soils are associated with more negative plant and soil water potentials during abiotic stress, inducing a greater resistance of xylem to cavitation and lower root systems than coarse soils. In contrast to some previous studies (Bosque-Sanchez et al. 2003; Gonzalez et al. 2009), in clay soil, biomass allocation between roots and shoots is considerably affected by water deficit (at moderate salinity) in quinoa, suggesting that, along with other adaptive mechanisms in response to abiotic stress, morphological features such as RSR should be studied. In close, comparing the forage crops (Figs. 8.3, 8.4, and 8.5), quinoa recorded higher dry root and shoot biomass for the same growth period and management (irrigation and fertilizer application), showing that this crop is more tolerant to the abiotic stresses and is likely to be successfully cultivated in the dry and saline conditions of the Kur-Araz lowlands. In harsh environments, soils cropped with quinoa rotation under traditional tillage would have greater potential for C sequestration and contribute to a better sustainability of soil resources (Hatfield 2013).

8.3.4 Allometric Relationship Between RM and SD of Plants

8.3.4.1 Short Review: Justification of a Novel Approach

There is increasing evidence of the importance of plasticity in plants under climate change in both natural and agricultural systems. The allometric relationships between plant organs in our study allows a link between plant structural development and primary physiological processes; hence, established relationships in ontogeny can be used as components of crops (e.g., crop model) and to estimate plant parameters that are difficult to measure (Niklas and Enquist 2004; Poorter et al. 2012a). Generally, plant morphology and green biomass are closely related aspects of the development of organs (e.g., root, stem, leaves, shoot). Plants biomass could be linked closely to the height of the plant and the stem thickness and, hence, water and nutrient management, as well as soil, meteorological, and management conditions. For instance, allometric parameters such as RSR and the harvest index (defined as a ratio of the seed mass to the aboveground biomass) depended on plant growing conditions (Tables 8.3 and 8.4), such as salinity and water deficit. Therefore, the ability of plants to adapt to the environment and abiotic stress conditions can be reflected in the allometric relationships (e.g., Weiner 2004; Song et al. 2015).

Plant developmental responses to climate change are limited by the numbers of experiments that were conducted with aboveground organs of plants under physiologically relevant stress conditions. Furthermore, current crop selection is mainly focused on the shoot, whereas most major drivers of the yield gap affected by soil properties directly influence root system development. Cultivated soils are heterogeneous environments strongly influenced by internal and external factors, and the soil-plant relationship is associated with spatiotemporal variation (Strudley et al. 2008; Roger-Estrade et al. 2009). However, regardless of longstanding observations and intensive research over generations, the biology of roots has largely been ignored by mainstream plant scientists and has remained “the hidden half” of the plant body (Waisel et al. 2002). Furthermore, there are difficulties inherent in the study of plant root dynamics in the field, with elevated labor work requirements. The complexity is related to reliable estimates of root biomass and distribution parameters, separation of live from dead ones, division of roots between individuals, and studying fine roots (<1 mm) below a specific root diameter; hence, objective analysis of allocation patterns in the field are difficult to obtain. Therefore, there has been a tendency to determine root biomass by developing indirect methods that would allow total or fine root biomass and production to be predicted using data on easily monitored variables that are highly correlated to root dynamics (Vogt et al. 1998; Poorter et al. 2012a).

The variation in stem diameter (SD) is closely associated with plant growth, affecting abiotic stresses and soil environment and management; hence, SD is well acknowledged as a useful stress indicator and, has, therefore, been used for irrigation scheduling in numerous studies (e.g., review paper of Fernandez and Cuevas 2010).

Recently, in combination with other plant measurements, SD has been used to study fundamental mechanisms underlying whole plant function and growth. The main mechanism affecting SD and its variation is linked to differences in water content in stem tissues, originating from reversible shrinkage and swelling of dead and living tissues, and irreversible growth (De Swaef et al. 2015). Nevertheless, in the root system, the response to abiotic stresses varies with each plant growth stage, growing conditions including climatic and soil factors, agronomic and irrigation management, and the degree of tolerance of the species, even within the different cultivars of the same species (Schenk and Jackson 2002; Rahnama et al. 2011; Sanchez-Blanco et al. 2014).

The sizes and shapes of root systems tend to differ among cultivated and wild plant growth forms and to vary along climatic gradients in water-limited and salinity systems. Overall, it has been revealed that the SD of plant, along with its leaf area index, evapotranspiration, soil, stem and leave water potential, stomatal conductance, water use efficiency, and, consequently, the height and dry biomass (RM, SM, RSR) of various plants species, is adversely affected by salinity or drought, otherwise by combination of abiotic stresses, and decreases with soil or irrigation water salinity and water deficit, and increases with mineral fertilizer, irrigation, and organic amendments application (Cai et al. 2010; Pulvento et al. 2010; Amin 2011; Alvarez et al. 2012; Hirich et al. 2013; Souza Miranda et al. 2013; Algosaibi et al. 2015; Lima et al. 2015; Kaplan et al. 2016; Javed et al. 2017; Negrao et al. 2017). Similar to trees, root growth in cultivated plants is closely related to whole plant growth; hence, SD, which is located in the "border" of root and shoot, grows with development of the root and shoot system, is positively affected by watering and fertilizer application, and is negatively affected by drought and salinity (e.g., cited papers in previous paragraph). Hence, SD could be linked with stem height and root length and consequently the mass of plant organs (e.g., leaves, stem, and root). Generally, the relationships between plant height and SD could be used even for very small, non-woody vertical stems that are principally supported by hydrostatic pressure (Niklas 1993; Poorter et al. 2012a; Mamedov et al. 2016).

8.3.4.2 Relationship Between Root Biomass and Stem Diameter of Plants

In clay soil with heavy texture, higher salinity level, elevated pH, and hard germination rate, to investigate the relationship between SD and plant parameters (e.g., RM, root length), would be vital. Allometric differences (exponent or coefficient of equations) would be expected between the forage crops with different root systems (Figs. 8.2, 8.3, 8.4, and 8.5). Thus, the allometric relationship between mass of root and its basal diameter (e.g., RM and SD) was used to characterize the contribution of soil and environmental factors to plant development (Fig. 8.6), which could be used in crop management and crop models. Results showed that (1) there is a strong power relationship between RM and SD for all plants ($R^2 > 0.8$–0.9; $p < 0.001$),

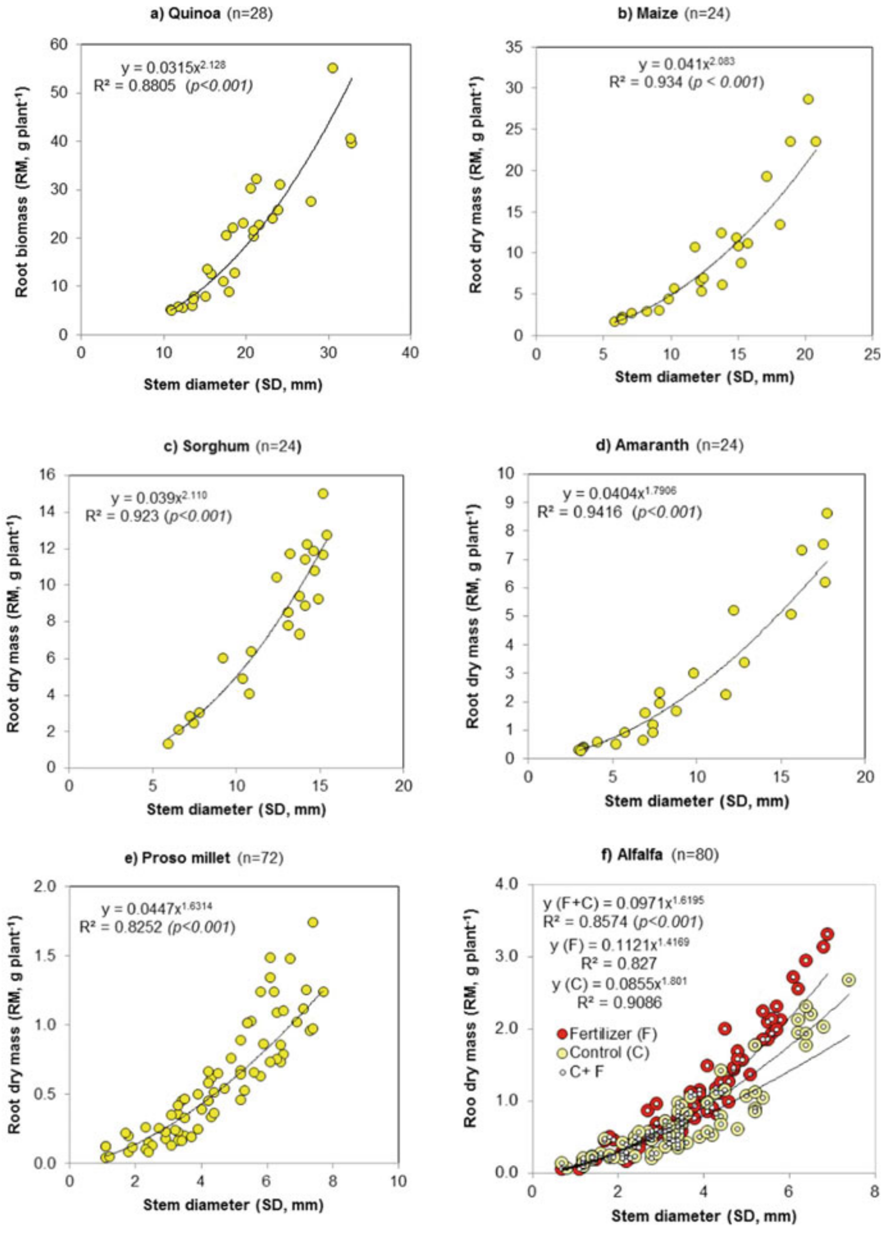


Fig. 8.6 Relationship between stem diameter (SD) and root dry biomass (RM) of plants grown in salt-affected clay soil at 0.6 × *I* irrigation regime (**a**) quinoa, (**b**) maize, (**c**) sorghum, (**d**) amaranth, (**e**) proso millet, and (**f**) alfalfa

(2) the exponent (1.61–2.11) of regression increases and the coefficient (0.019–0.10; $p < 0.001$) of regression decreases with the increase in RM of the plant (Fig. 8.6).

The regression relationship, which is related at least to similar soil and management condition, suggests that, in the same soil, various combined effects of abiotic stresses will be laid in the line of the defined curve, and using the SD at harvest, one can predict root dry biomass and its contribution to carbon sequestration or soil organic carbon/matter. The highest and lowest exponent of the equation (Fig. 8.6) were received for quinoa and alfalfa, respectively (quinoa > maize > sorghum > amaranth > proso millet > alfalfa). However, an opposite trend was noted for the coefficient of the equations, where alfalfa had the highest coefficient (Fig. 8.6), showing that the coefficients and exponents of power functions are related to plant species, biomass allocation, and SD. The power function described this relationship well ($R^2 \sim 0.9$, $p < 0.001$) and may allow understanding of the contribution of tested species and crop harvest stage on crop root, shoot, or leaf performance. Grouping the samples by fertility level of the soil (which is not discussed here), which is associated with abiotic stress (e.g. nutrient, water), may increase the R^2 of the relationship between RM and SD (Fig. 8.6f).

Using (1) the coefficient and exponent of the power relationship, one can explain the role of soil type or soil properties or stress on plant biomass (Fortier et al. 2015) and (2) easily measurable plant parameters, such as vegetative stage or plant height, to estimate the dry mass of plant organs can provide data required to estimate carbon accumulation rates and water and nutrient requirements for quinoa and other forage crops. Roots absorb water and nutrients from the soil and support aboveground shoot growth, whose yield depends on the growth of belowground root biomass. As the aboveground biomass of crops is usually harvested for grain, litter, or fuel, the roots form the main component of carbon input for soil carbon sequestration (Reddy et al. 1998; Poorter and Nagel 2000; Song et al. 2015; Faucon et al. 2017). Future research is needed to study the dynamics of root mass and SD at various stages of plant growth (e.g., phenological) to manage with allocation pattern of plants for better water and nutrient use and productivity under saline conditions.

8.3.4.3 Effect of Soil Texture and Plant Ontogeny on RSR

Plant biomass allocation shapes, reflecting plants respond to diverse selection stresses, and can vary greatly among both plant species and environmental conditions. Although variation in biomass allocation to leaves stems and roots been largely investigated, yet it is difficult to separate the single role of ontogenetic drift and environmental factors, since development of different organs, and plasticity in biomass allocation to varying resource accessibilities could be associated with both ontogenetic drift and environmental selection. Therefore, the roles of ontogenetic drift (differences in size) and environment influence (differences in developmental trajectory) as the basis for allocation responses to the environment were investigated in few studies and the results are inconsistent (McConnaughay and Coleman 1999; Hermans et al. 2006; Huang et al. 2009; Xie et al. 2012).

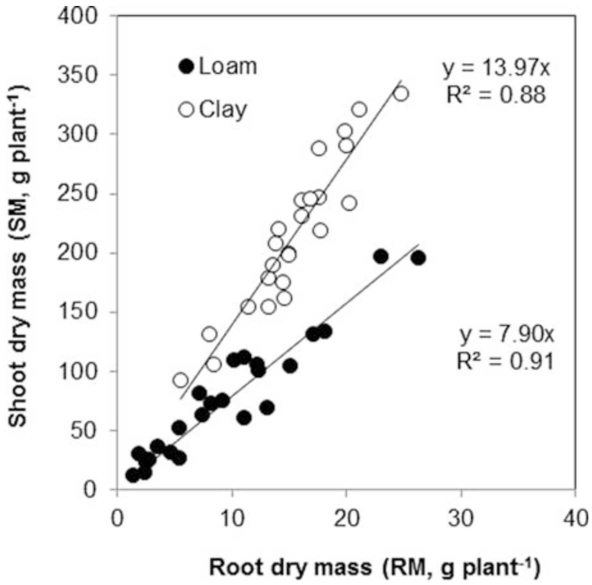


Fig. 8.7 Relationship between root and shoot dry biomass of quinoa grown in loam and clay soils

Although the production of shoot biomass by quinoa has been studied intensively, relatively little information is available about root biomass and architecture. Because of variations in root and shoot biomass associated with the soil and climatic conditions of the investigated region and stages of crop growth, the RSR can vary widely for quinoa species (e.g. references in Table 8.1). A meta-analysis of the literature about the effects of various environmental variables on the fraction of total plant biomass allocated to leaves, stem, and roots (e.g., RSR) showed that changes in allocation pattern are relatively strong when light or nutrient supply is varied, modest in the case of varying water supply, and almost negligible when the atmospheric CO_2 concentration is increased (Poorter and Nagel 2000). The authors also concluded that the absorbing and supporting organs should be studied separately to understand their role in resource gaining and/or response to resource limitation (Poorter and Nagel 2000). An analysis of the biomass distribution of 1200 plant species showed that, although plants strongly coordinate the relative sizes of leaves, stems, and roots, they were not ontogenetically fixed scaling exponents. Rather, the scaling exponents, as well as the biomass fractions with plant size, were dynamically shifting (Poorter et al. 2015).

Results regarding soil texture showed that water and fertilizer deficiency affected the growth of quinoa in loam soil and limited shoot the most. The plant height, SD, and total biomass (e.g., root, stem, leave) of quinoa grown in clay soils were higher in clay soil than in loam soil. Soil texture significantly changed the biomass allocation to shoot and roots; consequently, the RSR of quinoa planted in loam soil was about two times higher than the RSR of quinoa grown in clay soil (Fig. 8.7). For the vegetative organs, leaf to total biomass ratio was higher in clay soils, and root to total biomass was higher in loam soil (Table 8.6). However, for plants grown in

Table 8.6 Mean values of the ratios of leaf, stem, and root biomass to total biomass in loam and clay soils

Soil	Leaf to total biomass ratio[a]	Stem to total biomass ratio[a]	Root to total biomass ratio[a]	RSR[a]
Clay	0.057 a	0.49 a	0.067 b	0.072 b
Loam	0.042 b	0.48 a	0.110 a	0.124 a

[a]Within the same columns, means labeled with same letter are not significantly different at the $p < 0.05$ level ($n = 24$)

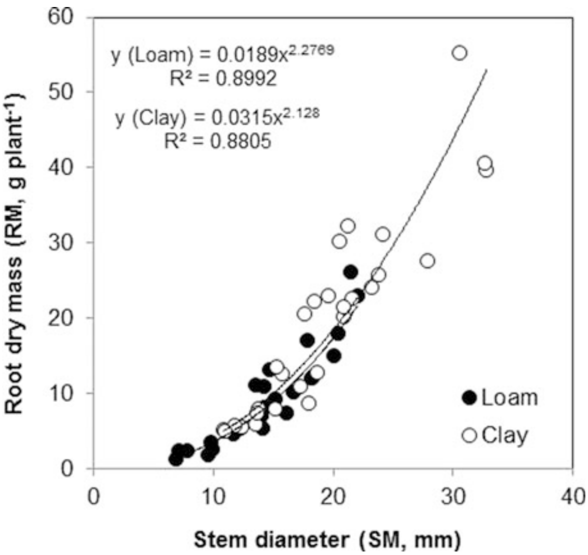


Fig. 8.8 Relationship between stem diameter (SD) and root dry biomass (RM) of quinoa grown in loam and clay soils

both soils, stem to total biomass ratio was not significantly different, and the relationship between SD and RM resulted in close scaling exponents (Figs. 8.7 and 8.8), showing similar allocations to the stems of the plants. The difference in ratios values between the soils revealed that the environmental factors (e.g., soil type) mostly controlled the biomass allocation to metabolically active roots and leaves, and ontogenetic capacity generally governed the biomass allocation to stems (e.g., Xie et al. 2012).

Differences in soil type and texture and moisture patterns may influence how quinoa roots respond to soil conditions. Soil texture gradients are based on the root contact, which creates a partial physical discontinuity at the soil-root interface for movement of water and nutrients from soil to roots (Fortier et al. 2015). The difference could be related to the fact that relatively more photosynthate was used by roots as they develop greater length to aid the plant in obtaining more water and nutrients. Under nutrient and water scarcity, the translocation of photoassimilates from shoots to roots increased with increased root sink strength, compared with that of the shoot (Fig. 8.8).

Limited literature analysis showed comparable consequences, signifying the role of the "optimal partitioning" and "plastic allometry" assumption, which suggests that plants may invest resources and may allocate carbon to improve their access to the limiting factor (Weiner 2004; Poorter et al. 2012a). Plastic allometry in the coarse root biomass of poplar plantations (Fortier et al. 2015) showed the existence of a strong regression relationship between diameter at breast height and coarse root biomass. The quality of links depends on soil type and fertility level (clay content, pH, N, P etc.). The authors, who originally evaluated relationship the between breast height and Rm for trees (e.g., poplars), stressed that RSR and coarse root biomass growth is both driven by ontogeny (size) and environment, reflecting the plasticity of the root system of mature poplars (Fortier et al. 2015). For soybean cultivars, allometric relations between stem height and mass and between proportions of leaves to the total shoot mass were stable in ontogeny; however, these relationships varied among crops grown in different soil type environments (Reddy et al. 1998).

Li et al. (2005), who used three levels of soil texture (sand, clay, and mixture) and evaporative demand (field, net, house) for the full cycle of cotton, reported that soil texture considerable influenced biomass allocation, and the long-term acclimation of the plant hydraulic system (hence, the plasticity of plant morphology) plays a major role in determining plant water and carbon economy. The authors showed that the root to leaf area ratio and the root-specific hydraulic conductance were higher and lower, respectively, in sandy soil than in clay soils (Li et al. 2005). In other experiments, soil texture significantly changed the development trajectories of leaf and root traits and the biomass allocation to leaves and roots, but not to stems, allowing the authors to conclude that biomass allocation to stems and root are related to ontogenetic drift and environmental factors (Wang et al. 2016). A recent study revealed that soil texture (e.g., sand vs. clay) had a significant effect on cotton xylem vessel diameter and the length of stems and roots, negatively affecting efficiency of the water transport system and decreasing stem height, SD and biomass and increasing RSR in course textured soil (Wang et al. 2016). The results of another experiment with the Jatropha root structure and growth in three soils varying in texture showed that the plant developed better, with increased SD, height and biomass, in sandy loam and clay loam soils than in sandy soil. It maintained relatively close RSR, being higher in sandy soil, and similar root system architecture; hence, the plant was still able to survive and maintain a favorable root-shoot relationship in all soils (Valdes-Rodriguez et al. 2013).

Razzaghi et al. (2012), who studied the effect of drought on quinoa in three soil types (sand, sandy loam, and sandy clay loam soil), stressed that soil texture had a significant effect on water and nutrient use efficiency and, therefore, the yield of quinoa. Soils with higher clay contents, water holding capacity, evapotranspiration, and yield are better suited to quinoa. An important feature of quinoa is that it can tolerate low soil quality better than other crops, being able to maintain a comparatively high production yield. In support of this conclusion, literature analysis shows that stem development is constrained by pant biomechanics rather than soil texture, which did not affect a shift in biomass allocation to stems. Further, the architecture of the primary root system and the variability in soil water or nitrogen availability did not change the stem to total mass ratio of plants, showing that the environmental medium affected the difference related to soil type (Reddy et al. 1998; Poorter and Nagel 2000; Price et al. 2007; Xie et al. 2012; Fortier et al. 2015; Razzaghi et al. 2012; Wang et al. 2016). In semi-arid and arid zone quinoa, shoot performance and yield (hence, root development) affected soil type and texture, and soil condition (Razzaghi et al. 2012; Noulas et al. 2015).

8.4 Conclusion

The responses of quinoa and forages to drought and salt stresses have much in common. The water limitations in water stress are very difficult for plants to tolerate and maintain their normal growth and development in clay soil with moderate salinity. These results suggest that quinoa could be recommended for large-scale cultivation in this semi-arid climatic region with limited water resources and degraded, salt-affected clay soil with crusting and swelling problems. However, more extensive field trials are required to select the best genotypes (e.g., cultivars) and to develop optimal protocols for their cultivation along with other forage crops. The sustainability of plants cropped in this area may be related to stress resistance (e.g., salinity, drought, and nutrients) and favorable agronomic characteristics (e.g., nutrient use efficiency, carbohydrate content, fatty acid content, survival, flowering, and biomass yield). Moreover, quinoa crop rotation could increase soil carbon sequestration and quality, and crop biomass utilization for carbon-neutral energy generation could considerably contribute to reduced atmospheric carbon emissions. The saline clay soils of the Kur-Araz lowland (1) appear to be suitable for cultivation of this multi-purpose agroindustrial crop and (2) could be reclaimed (as an economically alternative option) by quinoa cropping, since quinoa possesses (a) a unique native capability to survive with salinity and water scarcity based on its inherent low water requisite and (b) the ability to reoccupy rapidly its previous photosynthetic level and leaf area after a period of water stress (Jacobsen et al. 2003). This makes quinoa appropriate for growing in arid and semi-arid regions. Improved knowledge of the mechanisms of resistance of plants to adverse abiotic factors, and using GIS and remote sensing technology for environmental factors mapping and monitoring will help develop techniques for overcoming the constraints imposed by the severe environments that exist in the region.

The established unique relationship between SD and RM of annual crops grown in clay soils is vital for assessing the role of abiotic stresses (e.g., salinity, water and nutrient deficit) on plant performance; hence, increasing the accuracy of root biomass and carbon sequestration estimation will lead to a better understanding of carbon cycling in the soils and soil quality. In clay soil with high penetration resistance, large plant roots can contribute to the belowground biomass and carbon pool, having a positive effect on soil structure, rhizosphere processes, and terrestrial soil organic carbon reserves. Allometric relationships for plants, considering the contribution of environmental factors and ontogenic drift could be a useful tool for better agricultural management, as well as to evaluate performance of crop cultivars under given soil properties and management practices associated with various abiotic stresses. Selection of plant cultivars with different root systems should consider shifts between different root organs under various abiotic stress, rather than alterations in the division of biomass between the roots and shoot. Broader field tests should be done regarding to plant species, soil and salinity type, potential plant productivity, soil quality and root and biomass development, carbon sequestration perspective, and abiotic stress management, considering local variations in participation, water availability, and ecology.

Note Results of some ongoing studies (e.g., soil and plant and yield quality, ion translocation, major macro and micro element distribution in the plant organs, some allometric relationships between developmental rates of different organs, results of the study with ICBA line forages, image analysis on root, and some laboratory, pot, and green house tests) were not included in this paper.

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References

Acosta-Motos JR, Ortuno MF, Bernal-Vicente A, Diaz-Vivancos P, Sanchez-Blanco MJ, Hernández JA (2017) Plant responses to salt stress: adaptative mechanisms. Agronomy 7:18. https://doi.org/10.3390/agronomy7010018

Adolf VI, Jacobsen SE, Shabala S (2013) Salt tolerance mechanisms in quinoa (*Chenopodium quinoa* Willd.). Environ Exp Bot 92:43–54

Alandia G, Jacobsen SE, Kyvsgaard NC, Condori B, Liu F (2016) Nitrogen sustains seed yield of Quinoa under intermediate drought. J Agron Crop Sci 202:281–291

Algosaibi AM, El-Garawany MM, Badran AE, Almadini AM (2015) Effect of irrigation water salinity on the growth of quinoa plant seedlings. J Agric Sci 7:205–214

Alvarez S, Gomez-Bellot MJ, Castillo M, Banon S, Sanchez-Blanco MJ (2012) Osmotic and saline effect on growth, water relations, and ion uptake and translocation in Phlomis purpurea plants. Environ Exp Bot 78:138–145

Alvarez-Flores R, Winkel T, Nguyen-Thi-Truc A, Joffre R (2014) Root foraging capacity depends on root system architecture and ontogeny in seedlings of three Andean Chenopodium species. Plant Soil 380:415–428

Amin MH (2011) Effect of different nitrogen sources on growth, yield and quality of fodder maize (Zea mays L.). J Saudi Soc Agric Sci 10:17–23

Aurita-Silva A, Jacobsen SE, Razzaghi F, Alvarez Flores R, Ruiz K, Morales A, Silva H (2015) Quinoa drought responses and adaptation, Chapter 2.4. In: Bazile D, Bertero D, Nieto C (eds) State of the art report on quinoa around the world in 2013. FAO/CIRAD, Santiago, Chile, pp 157–171

Bartels D, Sunkar R (2005) Drought and salt tolerance in plants. Crit Rev Plant Sci 24:23–58
Benjamin JG, Nielsen DC (2004) A method to separate plant roots from soil and analyze root surface area. Plant Soil 267:225–234
Bertero HD (2001) Effects of photoperiod, temperature and radiation on the rate of leaf appearance in Quinoa (Chenopodium quinoa) under field conditions. Ann Bot 87:495–502
Biondi S, Ruiz KB, Martinez Dominguez B, Zurita-Silva A, Orsini F, Antognoni F, Dinelli G, Marotti I, Gianquinto G, Maldonado S, Burrieza HP, Bazile D, Adolf VI, Jacobsen SE (2015) Tolerance to saline conditions, Chapter 2.3. In: Bazile D, Bertero D, Nieto C (eds) State of the art report on quinoa around the world in 2013. FAO/CIRAD, Santiago, Chile, pp 143–156
Bolinder MA, Angers DA, Belanger G, Michaud R, Laverdiere MR (2002) Root biomass and shoot to root ratios of perennial forage crops in eastern Canada. Can J Plant Sci 82:731–737
Bosque-Sanchez H, Lemeur R, Van Damme P (2000) Análisis ecofisiológico del cultivo de la quínua (Chenopodium quinoa Willd.) en condiciones de estrés de la sequía y la salinidad. Tropicultura 18:198–202
Bosque-Sanchez H, Lemeur R, Van Damme P, Jacobsen SE (2003) Ecophysiological analysis of drought and salinity stress of quinoa. Food Rev Intl 19:111–119
Cai H, Chen T, Liu H, Gao D, Zheng G, Zhang J (2010) The effect of salinity and porosity of sewage sludge compost on the growth of vegetable seedlings. Sci Hortic 124:381–386
Castroluna A, Ruiz OM, Quiroga AM (2014) Effects of salinity and drought stress on germination, biomass and growth in three varieties of *Medicago sativa* L. Avances en Investigacion Agropecuaria 18:39–50
Choukr-Allah R, Rao NK, Hirich A, Shahid M, Alshankiti A, Toderich K, Gill S, Butt K, Ur R (2016) Quinoa for marginal environments: toward future food and nutritional security in MENA and Central Asia regions. Front Plant Sci 7:1–11. (paper 346)
Claeys H, Inze D (2013) The agony of choice: how plants balance growth and survival under water-limiting conditions. Plant Physiol 162:1768–1779
Cocozza C, Pulvento C, Lavini A, Riccardi M, d'Andria R, Tognetti R (2013) Effects of increasing salinity stress and decreasing water availability on ecophysiological traits of Quinoa (Chenopodium quinoa Willd.) grown in a Mediterranean-type agroecosystem. J Agron Crop Sci 199:229–240
Daynes CN, Field DJ, Saleeba JA, Cole MA, McGee PA (2013) Development and stabilisation of soil structure via interactions between organic matter, arbuscular mycorrhizal fungi and plant roots. Soil Biol Biochem 57:683–694
De Swaef T, De Schepper V, Vandegehuchte MW, Steppe K (2015) Stem diameter variations as a versatile research tool in ecophysiology. Tree Physiol 35:1047–1061
Eisa S, Hussin S, Geissler N, Koyro HW (2012) Effect of NaCl salinity on water relations, photosynthesis and chemical composition of quinoa (Chenopodium quinoa Willd.) as a potential cash crop halophyte. Aust J Crop Sci 6:357–368
Esechie HA, Al-Barhi B, Al-Gheity S, Al-Khanjari S (2002) Root and shoot growth in salinity-stressed alfalfa in response to nitrogen source. J Plant Nutr 25:2559–2569
Estefan G, Sommer R, Ryan J (2013) Methods of soil, plant, and water Analysis. International Center for Agricultural Research in the Dry Areas (ICARDA), Beirut, 244p
Fageria NK (2013) The role of plant roots in crop production. CRC Press, Boca Raton, FL
Fageria NK, Moreira A (2011) The role of mineral nutrition on root crop growth of crop plants. Adv Agron 80:63–152
Fageria NK, Baligar VC, Clark RB (2006) Physiology of crop production. The Howarth Press, New York
FAO (2016) Climate change and food security: risks and responses. FAO, Rome, 110p
Faucon MP, Houben D, Lambers H (2017) Plant functional traits: soil and ecosystem services. Trends Plant Sci 22:385–394
Fernandez JE, Cuevas MV (2010) Irrigation scheduling from stem diameter variations: a review. Agric For Meteorol 150:135–151

Fitter A (2002) Characteristics and functions of root systems. In: Waisel Y, Eshel A, Beeckman T, Kafkafi U (eds) Plant roots: the hidden half, 3rd edn. Marcel Dekker, New York, pp 15–32

Fortier J, Truax B, Gagnon D, Lambert F (2015) Plastic allometry in coarse root biomass of mature hybrid poplar plantations. Bioenergy Res 8:1691–1704

Galvan-Ampudia CS, Testerink C (2011) Salt stress signals shape the plant root. Curr Opin Plant Biol 14:296–302

Geerts S, Mamani RS, Garcia M, Raes D (2006) Response of quinoa (Chenopodium quinoa Willd.) to differential drought stress in the Bolivian Altiplano: towards a deficit irrigation strategy within a water scarce region. In: Proceedings of the 1st international symposium on land and water management for sustainable irrigated agriculture, CD-Rom

Geerts S, Raes D, Garcia M, Vacher J, Mamani R, Mendoza J, Huanca R, Morales B, Miranda R, Cusicanqui J, Taboada C (2008) Introducing deficit irrigation to stabilize yields of quinoa (Chenopodium quinoa Willd.). Eur J Agron 28:427–436

Gomez-Pando LR, Ivarez-Castro RA, Eguiluz-De La Barra A (2010) Effect of salt stress on Peruvian germplasm of Chenopodium quinoa Willd.: a promising crop. J Agron Crop Sci 196:391–396

Gonzalez JA, Gallardo M, Hilal M, Rosa M, Prado FE (2009) Physiological responses of quinoa (Chenopodium quinoa Willd.) to drought and waterlogging stresses: dry matter partitioning. Bot Stud 50:35–42

Gonzalez JA, Bruno M, Valoy M, Prado FE (2011) Genotypic variation of gas exchange parameters and leaf stable carbon and nitrogen isotopes in ten quinoa cultivars grown under drought. J Agron Crop Sci 197:81–93

Gray SB, Brady SM (2016) Plant developmental responses to climate change. Dev Biol 419:64–77

Hamed KB, Ellouzi H, Talbi OZ, Hessini K, Slama I, Ghnaya T, Munne Bosch S, Savoure A, Abdelly C (2013) Physiological response of halophytes to multiple stresses. Funct Plant Biol 40:883–896

Hariadi Y, Marandon K, Tian Y, Jacobsen SE, Shabala S (2011) Ionic and osmotic relations in quinoa (Chenopodium quinoa Willd.) plants grown at various salinity levels. J Exp Bot 62:185–193

Hatfield JL (2013) Climate change: challenges for future crop adjustments. In: Climate change and plant abiotic stress tolerance, vol 1. Wiley-VCH Verlag GmbH, pp 1–26

Hermans C, Hammond JP, White PJ, Verbruggen N (2006) How do plants respond to nutrient shortage by biomass allocation? Trends Plant Sci 11:610–617

Hirich A (2013) Using deficit irrigation with treated wastewater to improve crop water productivity of sweet corn, chickpea, fava bean and quinoa. Moroccan Rev Agron Vet Sci 2:15–22

Hirich A, Choukr-Allah R, Jacobsen SE, El-Yousfi L, El-Omari H (2012a) Using deficit irrigation with treated wastewater in the production of quinoa (Chenopodium quinoa Willd.) in Morocco. Revista Cientifica UDO Agricola 12:570–583

Hirich A, Choukr-Allah R, Ragab R, Jacobsen SE, El-Youssfi L, El-Omari H (2012b) The SALTMED model calibration and validation using field data from Morocco. J Mater Environ Sci 3:342–359

Hirich A, Choukr-Allah R, Jacobsen SE (2013) The combined effect of deficit irrigation by treated wastewater and organic amendment on quinoa (Chenopodium quinoa Willd.) productivity. Desalin Water Treat 52:2208–2213

Hirich A, Choukr-Allah R, Jacobsen SE (2014a) Deficit irrigation and organic compost improve growth and yield of quinoa and pea. J Agron Crop Sci 200:390–398

Hirich A, Choukr-Allah R, Jacobsen SE (2014b) Quinoa in Morocco–effect of sowing dates on development and yield. J Agron Crop Sci 200:371–377

Hirich A, Jelloul A, Choukr-Allah R, Jacobsen SE (2014c) Saline water irrigation of quinoa and chickpea: seedling rate, stomatal conductance and yield responses. J Agron Crop Sci 200:378–389

Huang YX, Zhao XY, Zhou DW, Zhao HL, Zhang HX et al (2009) Allometry of Salsola collina in response to soil nutrients, water supply and population density. Nord J Bot 27:539–547

Hudek C, Stanchi S, D'Amico M, Freppaz M (2017) Quantifying the contribution of the root system of alpine vegetation in the soil aggregate stability of moraine. Int Soil Water Conserv Res 5:36–42

Islam MS, Akhter MM, El-Sabagh A, Liu LY, Nguyen NT, Ueda A et al (2011) Comparative studies on growth and physiological responses to saline and alkaline stresses of Foxtail millet (Setaria italica L.) and Proso millet (Panicum miliaceum L.). Aust J Crop Sci 5:1269–1277

Ismailov AI (2013) Soil resources of Azerbaijan. In: Yigini Y, Panagos P, Montanarella L (eds) Soil resources of mediterranean and caucasus countries extension of the European soil database. Publications Office EU, Luxembourg, pp 16–36

Jacobsen SE, Mujica A, Jensen CR (2003) The resistance of quinoa (Chenopodium quinoa Willd.) to adverse abiotic factors. Food Rev Intl 19:99–109

Jacobsen SE, Liu F, Jensen CR (2009) Does root-sourced ABA play a role for regulation of stomata under drought in quinoa (Chenopodium quinoaWilld.). Sci Hortic 122(2):281–287

Javed Q, Wu Y, Azeem A, Ullah I (2017) Evaluation of irrigation effects using diluted salted water based on electrophysiological properties of plants. J Plant Interact 12:219–227

Kaplan M, Baran O, Unlukara A, Kale H, Rslan M, Kara K, Beyzi SB, Konca Y, Ulas A (2016) The effects of different nitrogen and irrigation levels on yield, nutritive value, fermentation and gas production of corn silage. Turkish J Field Crops 21:101–109

Karyotis T, Iliadis C, Noulas C, Mitsibonas T (2003) Preliminary research on seed production and nutrient content for certain quinoa varieties in a saline–sodic soil. J Agron Crop Sci 189:402–408

Klute A (ed) (1986) Methods of soil analysis, Part 1, 2nd edn. Argonomy monograpph No. 9. ASA and SSSA, Madison, WI

Koevoets IT, Venema JH, Elzenga JTM, Testerink C (2016) Roots withstanding their environment: exploiting root system architecture responses to abiotic stress to improve crop tolerance. Front Plant Sci 7:1335. https://doi.org/10.3389/fpls.2016.01335

Lavini A, Polenta C, Deandra R, Riccardo M, Chukor-Allah R, Belabor O et al (2014) Quinoa's potential in the Mediterranean region. J Agron Crop Sci 200:344–360

Li Y, Xu H, Cohen S (2005) Long-term hydraulic acclimation to soil texture and radiation load in cotton. Plant Cell Environ 28:492–499

Lima GS, Nobre RG, Gheyi HR, Soares LAA, Silva EM (2015) Irrigation water salinity and nitrogen doses affect the cultivation of castor bean (Ricinus communus L.) at different phonological stages. Aust J Crop Sci 9:870–878

Lux A, Rost TL (2012) Plant root research: the past, the present and the future. Ann Bot 110:201–204

Maas EV, Hoffman GJ (1977) Crop salt tolerance – current assessment. J Irrig Drain Div ASCE 103:115–134

Mamedov AI, Gasimova Kh, Farzaliyev V, Toderich K, Ali-zade VM (2016) Forage crop research in a changing climate. Proceedings of international conference "innovative approaches to conservation of biodiversity." Baku, ANAS, 6 p, CDRom

McConnaughay KDM, Coleman JS (1999) Biomass allocation in plants: ontogeny or optimality? A test along three resource gradients. Ecology 80:2581–2593

Munns R (2002) Comparative physiology of salt and water stress. Plant Cell Environ 25:239–250

Munns R, Gilliham M (2015) Salinity tolerance of crops–what is the cost? New Phytol 208:668–673

Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59:651–681

Negrao S, Schmockel SM, Tester M (2017) Evaluating physiological responses of plants to salinity stress. Ann Bot 119:1–11

Niklas KJ (1993) The allometry of plant reproductive biomass and stem diameter. Am J Bot 80:461–467

Niklas KJ, Enquist BJ (2004) Canonical rules for plant organ biomass partitioning and annual allocation. Am J Bot 89:812–819

Noulas C, Karyotis T, Iliadis C (2015) Greece. Experimentation and current distribution, Chapter 6.1.6. In: Bazile D, Bertero D, Nieto C (eds) State of the art report on quinoa around the world in 2013. FAO/CIRAD, Santiago, Chile, pp 492–510

Nurbekov A, Kassam A, Sydyk D, Ziyadullaev Z, Jumshudov I, Muminjanov H, Feindel D (2016) Conservation agriculture in irrigated areas of Azerbaijan, Kazakhstan and Uzbekistan. FAO, Ankara, 84p

Omami EN, Hammes PS (2006) Interactive effects of salinity and water stress on growth, leaf water relations, and gas exchange in amaranth (Amaranthus spp.). N Z J Crop Hortic Sci 34:33–44

Page AL, Miller RH, Keeney DR (eds) (1986) Methods of soil analysis, Part 2, Agronomy monograph No. 9, 2nd edn. ASA and SSSA, Madison, WI

Poorter H, Nagel OW (2000) The role of biomass allocation in the growth response of plants to different levels of light, CO_2, nutrients and water: a quantitative review. Aust J Plant Physiol 27:595–607

Poorter H, Niklas KJ, Reich PB, Oleksyn J, Poot P, Mommer L (2012a) Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. Tansley review. New Phytol 193:30–50

Poorter H, Buhler J, van Dusschoten D, Climent J, Postma JA (2012b) Pot size matters: a meta-analysis of the effects of rooting volume on plant growth. Func Plant Biol J 39:839–850

Poorter H, Jagodzinski AM, Ruiz-Peinado R, Kuyah S, Luo Y, Oleksyn J, Usoltsev VA et al (2015) How does biomass distribution change with size and differ among species? An analysis for 1200 plant species from five continents. New Phytol 208:736–749

Price C, Munns R (2016) Growth analysis: a quantitative approach. In: Munns R, Schmidt S, Beveridge C (eds). Plant in action. Australian Society of Plant Scientists, New Zealand Society of Plant Biologists, and New Zealand Institute of Agricultural and Horticultural Science

Price CA, Enquist BJ, Savage VM (2007) A general model for allometric covariation in botanical form and function. Proc Natl Acad Sci U S A 104:13204–13209

Pulvento C, Riccardi M, Lavini A, D'Andria R, Iafelice G, Marconi E (2010) Field trial evaluation of two Chenopodium quinoa genotypes grown under rain-fed conditions in a typical Mediterranean environment in south Italy. J Agron Crop Sci 196:407–411

Pulvento C, Riccardi M, Lavini A, Iafelice G, Marconi E, d'Andria R (2012) Yield and quality characteristics of quinoa grown in open field under different saline and non-saline irrigation regimes. J Agron Crop Sci 198:254–263

Qadir M, Quillerou E, Nangia V, Murtaza G, Singh M, Thomas RJ, Drechsel P, Noble AD (2014) Economics of salt-induced land degradation and restoration. Nat Res Forum 38:282–295

Rahnama A, Munns R, Poustini K, Watt M (2011) A screening method to identify genetic variation in root growth response to a salinity gradient. J Exp Bot 62:69–77

Razzaghi F, Ahmadi SH, Adolf VI, Jensen CR, Jacobsen SE, Andersen MN (2011a) Water relations and transpiration of Quinoa (Chenopodium quinoa Willd.) under salinity and soil drying. J Agron Crop Sci 197:348–360

Razzaghi F, Ahmadi SH, Jacobsen SE, Jensen CR, Andersen MN (2011b) Effects of salinity and soil–drying on radiation use efficiency, water productivity and yield of quinoa (Chenopodium quinoa Willd.). J Agron Crop Sci 198:173–184

Razzaghi F, Plauborg F, Jacobsen SE, Jensen CR, Andersen MN (2012) Effect of nitrogen and water availability of three soil types on yield, radiation use efficiency and evapotranspiration in field-grown quinoa. Agric Water Manag 109:20–29

Reddy VR, Pachepsky YA, Whisler FD (1998) Allometric relationships in field grown soybean. Ann Bot 82:125–131

Rengasamy P (2010) Soil processes affecting crop production in salt affected soils. Funct Plant Biol 37:613–620

Roger-Estrade J, Richard G, Dexter AR, Boizard H, de Tourdonnet S, Bertrand M, Caneill J (2009) Integration of soil structure variations with time and space into models for crop management. A review. Agron Sustain Dev 29:135–142

Roumet C, Birouste M, Picon-Cochard C, Ghestem M, Osman N, Vrignon-Brenas S, Cao K, Stokes A (2016) Root structure–function relationships in 74 species: evidence of a root economics spectrum related to carbon economy. New Phytol 210:815–826
Roy SJ, Negrao S, Tester M (2014) Salt resistant crop plants. Curr Opin Biotechnol 26:115–124
Ruiz KB, Biondi S, Oses R, Acuna-Rodriguez IS, Antognoni F, Martinez-Mosqueira EA et al (2014) Quinoa biodiversity and sustainability for food security under climate change. Agron Sustain Dev 34:349–359
Ruiz KB, Aloisi I, Del Duca S, Canelo V, Torrigiani P, Silva H et al (2016) Salares versus coastal ecotypes of quinoa: salinity responses in Chilean landraces from contrasting habitats. Plant Physiol Biochem 101:1–13. https://doi.org/10.1016/j.plaphy.2016.01.010
Sanchez-Blanco MJ, Alvarez S, Ortuno MF, Ruiz-Sanchez MC (2014) Root system response to drought and salinity: root distribution and water transport. In: Morte A, Varma A (eds) Soil biology. Springer, Berlin, pp 325–352
SAS Institute 1995 SAS guide for personal computers. 6.07, SAS Inst., Cary, NC
Schenk HJ, Jackson RB (2002) Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems. J Ecol 90:480–494
Schlick G, Bubenheim DL (1996) Quinoa: candidate crop for NASA's controlled ecological life support systems. In: Janick J (ed) Progress in new crops. ASHS Press, Arlington, VA, pp 632–640
Shalhevet J, Huck MG, Schoeder BP (1995) Root and shoot responses to salinity in maize and soybean. Agron J 87:512–517
Six J, Bossuyt H, De Gryze S, Denef K (2004) A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res 79:7–31
Skinner RH, Comas LH (2010) Root distribution of temperate forage species subjected to water and nitrogen stress. Crop Sci 50:2178–2185
Smith S, De Smet I (2012) Root system architecture: insights from Arabidopsis and cereal crops. Philos Trans R Soc Lond B Biol Sci 367:1441–1452
Soliz-Guerrero JB, De Rodriguez D, Rodriguez-Garcia R, Angulo-Sanchez JL, 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
Song Y, Rui Y, Birch C, Hanan J (2015) Allometric relationships of maize organ development under different water regimes and plant densities. Plant Prod Sci 18:1–10
Souza Miranda R, Ruppenthal V, Sousa Lopes L, Fontenele Vieira C, Braga Marques V, Alves Bezerra M, Feitosa Lacerda C (2013) Phosphorus fertilization improves soybean growth under salt stress. Int J Plant Anim Sci 2:21–29
Stikic R, Jovanovic Z, Marjanovic M, Dordevic S (2015) The effect of drought on water regime and growth of quinoa (Chenopodium quinoa Willd.). Ratarstvo i povrtarstvo. Field Veg Crops Res 52:80–84
Strudley MW, Green TR, Ascough JC (2008) Tillage effects on soil hydraulic properties in space and time: state of the science. Soil Tillage Res 99:4–48
Valdes-Rodriguez OA, Sanchez-Sanchez O, Perez-Vazquez A, Caplan JS, Danjon F (2013) Jatropha curcas L. Root structure and growth in diverse soils. Sci World J. Article ID 827295, 9 p. doi:https://doi.org/10.1155/2013/827295
Vasilakoglou I, Dhima K, Karagiannidis N, Gatsis T (2011) Sweet sorghum productivity for biofuels under increased soil salinity and reduced irrigation. Field Crops Res 120:38–46
Vogt KA, Vogt DJ, Bloomfield J (1998) Analysis of some direct and indirect methods for estimating root biomass and production of forests at an ecosystem level. Plant Soil 200:71–89
Waisel T, Eshel A, Beeckman T, Kafkafi U (2002) Plant roots: the hidden half, 3rd edn. Marcel Dekker, New York/Basel
Wang Z, Xie J, Li YJ (2016) Safety-efficiency trade-offs in the cotton xylem: acclimatization to different soil textures. Arid Land 8:443–452
Weiner J (2004) Allocation, plasticity and allometry in plants. Perspect Plant Ecol Evol Syst 6:207–215

Wu Q, Pages L, Wu J (2016a) Relationships between root diameter, root length and root branching along lateral roots in adult, field-grown maize. Ann Bot 117:379–390

Wu G, Peterson AJ, Morris CF, Murphy KM (2016b) Quinoa seed quality response to sodium chloride and sodium sulfate salinity. Front Plant Sci 7:790. https://doi.org/10.3389/fpls.2016.00790

Xie JB, Tang LS, Wang ZY et al (2012) Distinguishing the biomass allocation variance resulting from ontogenetic drift or acclimation to soil texture. PLoS One 7:e41502

Yazar A, Incekaya C, Sezen SM, Jacobsen SE (2015) Saline water irrigation of quinoa (Chenopodium quinoa) under Mediterranean conditions. Crop Pasture Sci 66:993–1002

Zegada-Lizarazu W, Zatta A, Monti A (2012) Water uptake efficiency and above- and belowground biomass development of sweet sorghum and maize under different water regimes. Plant Soil 351:47–60

Chapter 9
Cañahua (*Chenopodium pallidicaule*): A Promising New Crop for Arid Areas

Juan Pablo Rodriguez, Sven-Erik Jacobsen, Christian Andreasen, and Marten Sørensen

Abstract The genus *Chenopodium* L. is a large group of plants of the amaranth, quinoa and spinach family (the Amaranthaceae), contributing significantly as providers of food. Another species belonging to this family is the neglected and underutilized Andean grain species cañahua (*Chenopodium pallidicaule* Aellen). The grains are small and characterized by a low content of saponins and a high content of proteins with essential amino acid and high content of omega-6 fatty acid and essential minerals. The flour is a good alternative to wheat for people with coeliac problems.

The crop is grown organically by small-scale farmers in the highland of Bolivia and Peru, where growing conditions are harsh because of low fertility, salinity, strong winds and great variation in temperatures. It grows in dry, semi-arid to semi-desert land. It is used as staple foods in rural and urban diet as well as a fodder plant. Cañahua is a robust crop usually sown in the spring with 40–50 cm between rows. No pests or diseases seem to be able to affect its development and growth significantly. However, yields are usually low (*ca* 1100 kg ha^{-1}) depending of growing conditions and variety/landrace. For some varieties and landraces, seed shattering before harvest can be a problem, especially under extreme weather condition which is not rare in the region.

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Cañahua grains and flour has a great potential for export because it can be cropped organically under extreme condition and has a high nutritional value. Unfortunately, only a few know about the crop and its qualities, and it has not been bred intensively to improve yields so far.

Keywords Andean seed · Organic agriculture · NUS · Protein crop

9.1 Introduction

Food provision and nutritional security are challenges for the next generations. It is expected that by 2050 the Earth will have 9 billion inhabitants and 11 billion by the end of the century (FAO 2017). Monoculture and extensive agriculture are changing the urban and rural food systems (Khoury et al. 2014), and climate change and abiotic stresses are affecting crop productivity in many agro-ecological regions resulting in lower yields (St.Clair and Lynch 2010; Newton et al. 2011). Marginal crops could become significant resources to overcome some climate change and hazardous environmental constraints (Jacobsen et al. 2013, 2015).

Crops belonging to the Amaranthaceae are alternatives for arid ecosystems, such as the highly demanded quinoa (*Chenopodium quinoa* Willd.), which is now introduced in many countries. Quinoa is traditionally grown in rural communities of the Andean highland in South America. Recently it has been introduced to Europe, Africa and Central Asia (Alandia et al. 2016; Jacobsen 2003). The development and adoption of new quinoa varieties with low content of saponins will take time, but the close relative of quinoa, named cañahua (*C. pallidicaule*), cañihua, cañawa or kañiwa, already has a low content of saponins and a high content of proteins. However, its semi-domesticated trait of seed shattering does reduce seed yield (Rodriguez et al. 2017).

Peru and Bolivia are presently the only cañahua producers (Gade 1970; Apaza 2010; Estaña and Muñoz 2012). However, the crop has got increasing attention due to its gluten-free seeds and the low content of saponins and high nutritional value (Rastrelli et al. 1996; Repo-Carrasco et al. 2003; Penarrieta et al. 2008; Repo-Carrasco-Valencia et al. 2009, 2010). This chapter will provide the latest findings and developments of the cañahua and highlight why the crop is important for rural households in marginal and remote regions. We will discuss why this Andean species holds a strong potential due to low fertilizer requirements and as a provider of a highly nutritious grain for food and economic profit for small-holder farmers. Cañahua is produced organically by small-scale farmers.

9.2 Socio-economic Importance

The cañahua has tiny grains (0.66 ± 0.03 mg seed^{-1}) that are commonly consumed by rural households on the Bolivian and Peruvian Altiplano up to 3.200 m a.s.l. Currently, it is not frequently included in the urban food culture due to lack of promotion and food education (Jacobsen et al. 2015). Compared to quinoa, only small quantities of cañahua are traded. Commercially the cañahua is found branded as 'gluten-free grain', 'baby quinoa grain' from 'organic Andean agriculture' from Peru and Bolivia. Lately, the grain crop has attracted the attention from NASA (the National Aeronautics and Space Administration, USA) due to its high nutritional and functional value as food for astronauts (ABI 2017). In Bolivia, cañahua is cultivated across the Altiplano ecozone in the departments of La Paz, Oruro, Cochabamba, Potosi and Tarija, and in Peru across the Sierra in Cusco, Ayacucho, Junin and Huaraz (Bravo et al. 2010; Apaza 2010; Rojas et al. 2010).

Cañahua is a neglected crop, and little effort has been invested boosting it at local markets (Giuliani et al. 2012). Farmers often chose to grow more economically attractive crops. This tendency affects the cañahua seed production and increases its genetic erosion resulting in fewer landraces (Rojas et al. 2010; Brown and Hodgkin 2015). Peru has a larger area with cañahua than Bolivia. Breeding efforts remain few, and seed yields per plant have not increased in the last 10 years (Fig. 9.1).

Compared to quinoa, the value chain of cañahua from the producers to the rural and urban market is not yet well developed. Rojas et al. (2004) stressed the risk of the genetic erosion of native cañahua varieties based on a survey of 467 rural households of the Titicaca Lake in Bolivia. 22% of the interviewed households grew cañahua; 84% were cultivated for auto-consumption, 8% for selling, 6% produced seeds for sowing and 1% for barter. Albeit the inclusion of cañahua-based products in Bolivian urban markets is low, it does, however, hold great perspectives for the food industry (Rojas et al. 2010). The export of cañahua is small as only a few consolidated clusters of producers exist in Cochabamba and Oruro (Carrasco and Soto 2010). The price of cañahua grain varies somewhat between the rural fairs of La Paz, Oruro, and Cochabamba in Bolivia (USD 2.2–2.9 kg^{-1}) and Puno and Juliaca in Peru (USD 2.8–3.1 kg^{-1}) (Giuliani et al. 2012).

Cañahua is essential for the rural livelihoods regarding food security, nutrition and self-reliance. Its promotion should be based upon its natural assets and as an important part of the traditional knowledge of rural livelihoods (Catacora 2017; Rojas et al. 2010). Soto et al. (2017) stressed that urban nutritional food security should be strengthened by using Andean grains. Cañahua grains contain flavonoids and phenolic compounds with high antioxidant activity and have a high content of dietetic fibres. Also, the inclusion of cañahua in food products can be beneficial for people with problems of cholesterol (Aro et al. 2017).

Peru produces six times more cañahua than Bolivia (Fig. 9.1) and produces higher grain yields ha^{-1} than Bolivia. However, compared to quinoa, the yields are low in both countries probably because cañahua still is cultivated under traditional techniques and on small plots. Farmers often replace cañahua with barley (*Hordeum vulgare* L.) and oat (*Avena sativa* L.) as fodder crops. Low-cost cañahua is an alternative source for minor livestock feed (Calle 2004; Cortez 2016). Cañahua grains are easy to use as both grain and grain husk.

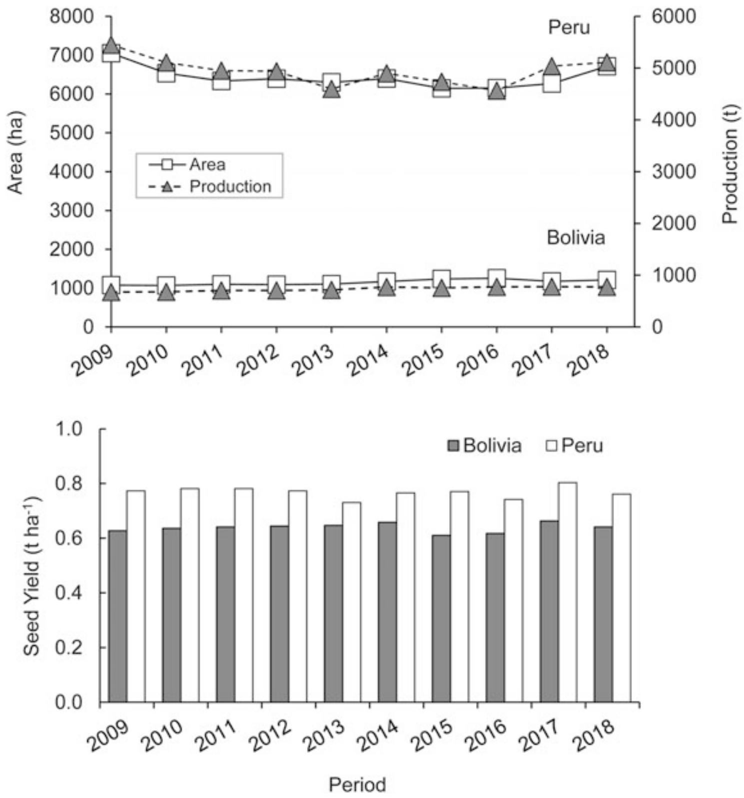

Fig. 9.1 Area, seed production, and seed yield of cañahua in Bolivia (INE 2018) and Peru (SIEA 2018)

9.3 Botany and Domestication

Cañahua and quinoa belong to the genus *Chenopodium* L., which includes150 species of herbaceous flowering plants. Cañahua originated in the Andes of southern Peru and Bolivia. It was domesticated by the Tiahuanacu culture in the Collao highland of Bolivia. In Peru and Bolivia, it is an important crop in the high plateau (3800–4300 m a.s.l.) due to its cold tolerance.

Cañahua plants produce thousands of dry, single-seeded fruits on small inflorescences. 15–35% of the seeds are lost due to seed shattering that occurs during flowering and physiological maturity (Rodriguez et al. 2017). The fruit produced by the plant is usually known as ‘grain’ by agronomists and horticulturalists, but morphologically it is an achene (Gorinstein et al. 2005). The panicle-shaped inflorescence has small lateral inflorescence branches, which is a common feature in both cultivated and wild Amaranthaceae (Spehar and Santos 2002).

On the Bolivian and Peruvian Altiplano, two different growth habit types are known: the ‘Saihua’ and ‘Lasta’ (Table 9.1). The first type is widespread in the rural communities and provides the highest seed yield (Calle 1980; Maydana 2010; Rodriguez et al. 2017). A third growth habit type is called ‘Pampalasta’. Farmers only sow this kind if there is a lack of the other types and lack of other food sources in seasonally extreme cases (Estaña and Muñoz 2012; Serrano 2012). The non-uniform maturation and tendency to seed shattering are traits revealing its semi-domesticated status (Rodriguez et al. 2017).

9.4 Genetic Diversity

Cañahua is not distributed outside the Altiplano of Bolivia (north of Oruro and close to Cochabamba) and Peru (Ayaviri, Puno, Cusco, Ayacucho and Junin). The geographic distribution of cañahua in Bolivia is smaller than that of the quinoa and is currently conserved by the Bolivian National Germplasm Bank of INIAF (Galluzzi and López Noriega 2014). There is a considerable genetic variability in cañahua. It is distributed from 15°21′ of South Latitude in the Iñita Grande community (province of Camacho, Department of La Paz), to 21°28 of South Latitude in the Huancarani community of the province of Antonio Quijarro, Department of Potosi (Rojas et al. 2010). It is also grown from 66°08′ West Longitude in the Llaytani community of the Bolivar province, Department of Cochabamba, to 60°09′ West Longitude in the community of Picata (province of Camacho, Department of La Paz). The altitudinal distribution range varies from 3200 to 4200 m a.s.l.

The greatest variability of cañahua is in the lacustrine region of Lake Titicaca (Fig. 9.2). This area is considered the centre of origin and with the largest species diversity of Chenopods (Langlie et al. 2011) followed by the highlands of Cochabamba (province Bolivar), the northern bank of Lake Titicaca (province Camacho) and at the south end of the lake (Ingavi and Los Andes Province).

In Bolivia, it is cultivated in the provinces of Pacajes, Ingavi, Los Andes, Omasuyos, Camacho and Manco Kapac of the department of La Paz, in the provinces of Independencia, Tapacari and Bolivar of the Department of Cochabamba (Rojas et al. 2010; Galluzzi and López Noriega 2014). The greatest concentration of cañahua is in the north-western part of the Altiplano in the Department of Puno in Peru (Tapia 1997).

9.5 Nutritional Compounds

Nowadays great grains are used as an alternative food with high nutrient content and for people with coeliac problems. The population is used to eat conventional food and commonly carbohydrates from wheat-based products. Cañahua has been cultivated in the Andean region for thousands of years (Gade 1970). It is a diploid species

Table 9.1 Morphological description of cañahua growth habit types

Growth habit	Saihua	Lasta	Pampalasta
Local names	Choqos[a], Chhuqu[b], Chucayo[a]	Thasas[a]	Mamacañihua[c]
Description	*Erect:* few branches and upright.	*Branched semi-prostrate*: numerous branches	*Branched and prostrate:* its stems fallen or lines in which only their ends are upright
			

In [a]Quechua (Cuba 2005) and [b]Aymara (Alanoca 2006) the plant types 'Lasta' and 'Saihua' are semi-cultivated, while the 'Pampalasta' remains wild (Serrano 2012). [c]'Mamacañihua' is also found in rural communities in Puno, Peru (Estaña and Muñoz 2012)

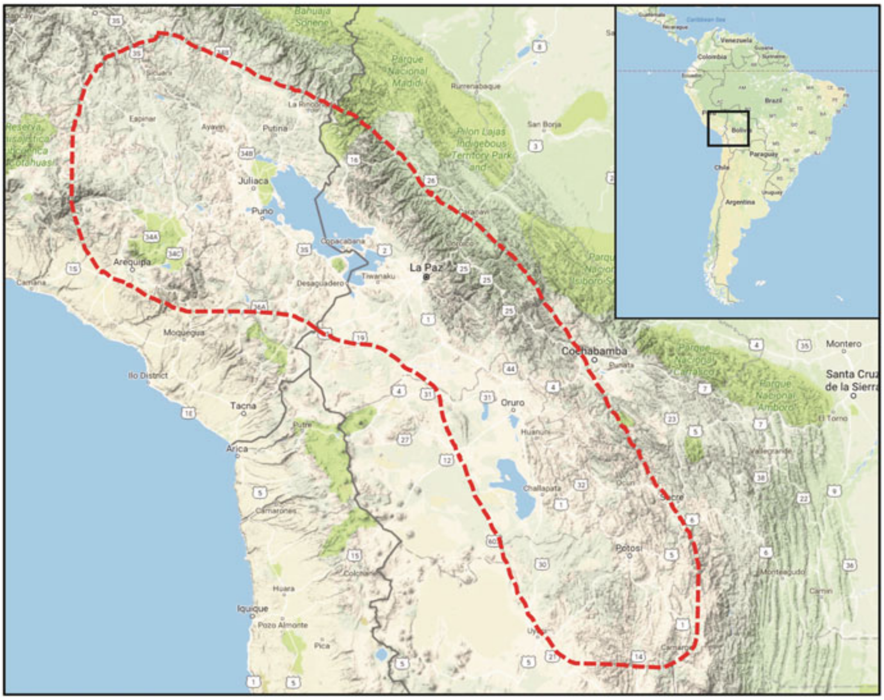

Fig. 9.2 Distribution of cañahua in the rural communities of Peru and Bolivia (Source: Map Data © Google, 2017)

($2n = 2x = 18$), a close relative of spinach, quinoa and amaranth (Jarvis et al. 2017). Cañahua is a highly nutritious seed crop which is rich in amino acid (lysine), unsaturated fatty acids (linolenic acid, linoleic acid), mineral composition as cofactors in antioxidant enzymes (calcium, iron, magnesium and zinc) and phenolic compounds with antioxidant power (Galvez et al. 2009; Repo-Carrasco-Valencia et al. 2010) (Table 9.2).

The World Health Organization (WHO) projected that diabetes will be the seventh leading cause of death in 2030 (WHO 2016). In the last 10 years, the prevalence of diabetes mellitus (DM) has increased rapidly in low-income countries. The National Health Information System (SNIS) in Bolivia estimated the prevalence of diabetes to be 6.6% in Bolivia, and 7% in Peru (Villena 2016; minsalud.gob.bo 2017). Overweight and obesity cause diabetes; however, annual per capita consumption of nutritional and healthy food crops like Andean grains (quinoa, cañahua, and amaranth) is low compared to wheat flour bakery products. In 2016 it was 1.5 kg $year^{-1}$ in Bolivia and 1.8 kg $year^{-1}$ in Peru (Filomeno 2017; Lanza Lobo 2017; MINAGRI 2017). Repo-Carrasco et al. (2003) and Galvez et al. (2009) recommended consumption and use of cañahua because of its important level of quercetin derivatives and low carbohydrate content to combat diabetes and overweight of children. Moreover, the content of essential minerals is higher in cañahua

Table 9.2 Nutritional composition of *Chenopodium pallidicaule* seeds

	Proximate compositions (mg/100 g DM)[a]				Minerals (mg/100 g DM)[b]				Essential amino acids (g/100 g protein)[c]					Fatty acids[d]		Phenolic compound (µg/g)
	Crude fat	Protein	CARB	Raw fibre	Ca	Mg	Fe	Zn	Lys	His	Leu	Met	Cys	Linoleic acid	Linolenic acid	Quercetin derivatives
Cañahua	**7.6**	**18.8**	**63.4**	**6.1**	**66.45**	**3.36**	**2.47**	**2.83**	**5.6**	**2.7**	**6.1**	**3**	**1.6**	**39.2**	**1.2**	**943**
Quinoa	6	14.4	72.6	4.0	67.55	3.92	2.61	2.7	5.6	2.7	6.1	3.1	1.7	38.9	24.3	1131
Amaranth	7.6	14.5	71.5	5.0	180.0	269	9.2	4.2	5.6	2.4	5.4	3.8	2.3	42.8	0.8	ND
Wheat	2.6	10.5	74.1	2.5	43.11	4.9	2.64	3.3	3.2	2.2	7.5	3.6	2.5	54.2	3.5	ND
Corn, yellow	4.9	11.1	80.2	2.1	11.43	n.d.	2.72	n.d.	–	12.3	2.1	1.8	–	56.6	1.93	ND
Rice	2.2	9.1	71.2	10.2	11.43	n.d.	1.01	n.d.	2.8	2	6.7	1.3	2.2	0.114	0.024	
Requirements for adults									**4.5**	**1.5**	**5.9**	**1.6**	**0.6**			

Bold characters highlight the nutritional content of cañahua grain in essential amino acids when compared to other grains and with the requirements for adults
DM dry matter, *CARB* carbohydrates, *Lys* lysine, *His* histidine, *Leu* leucine, *Met* metionine, *Cys* cysteine

[a]Repo-Carrasco et al. (2003), Gross et al. (1989), Mundigler (1998), Nascimento et al. (2014), Kent (1983), Singh and Singh (2011), Montealvo et al. (2005)

[b]Alvarez-Jubete et al. (2009), Repo-Carrasco et al. (2003), Gallego et al. (2014)

[c]Repo-Carrasco et al. (2003)

[d]Budin et al. (1996), Jahaniaval et al. (2000), Gallego et al. (2014)

[e]Galvez et al. (2009)

grains than in wheat and rice (Alvarez-Jubete et al. 2009; Gallego et al. 2014). Cañahua grains have a high content of essential amino acids and contain the two omega-6 fatty acids linoleic and linolenic acid (Budin et al. 1996; Jahaniaval et al. 2000; Repo-Carrasco et al. 2003; Gallego et al. 2014).

9.6 Ecology and Botanical Geography

According to Catacora (2017), cañahua originates from the Titicaca Lake Basin between Peru and Bolivia. Bolivia holds a significant collection of cañahua, the Germplasm Seed Bank of the National Institute of Forest and Agriculture Innovation (INIAF). With 801 cañahua seed accessions, the collection is the largest compared to the 341 cañahua accessions Peru conserves in the Banco de Germoplasma del Centro de Investigación y Producción Camacani in Puno (Mamani 2013).

The genus *Chenopodium* comprises more than 150 species, including leaf vegetables commonly seen in the urban and rural markets, i.e., spinach (*Spinacia oleracea* L.). The genus is now placed in the Amaranth family (Amaranthaceae) *sensu lato* (APG II system). This family also includes the leaf and grain Amaranths (*Amaranthus* L. spp.), the Quinoa (*Chenopodium quinoa* Willd.) and the Cañahua (*C. pallidicaule* Aellen) (Fuentes-Bazan et al. 2012; Cruz Torres et al. 2013). Chenopod species have been cultivated as food crops in millennia in North, Central and South America. The pit seed goosefoot (*C. berlandieri* Moq. subsp. *jonesianum* B.D.Sm.) was intensively cultivated by indigenous agriculturalists in the Eastern Northern America before the domestication of maize (*Zea mays* subsp. *mays* L.) (Fritz et al. 2017; Bruno 2006). In Central America, huauzontle (*C. nuttalliae* Saff.) was cultivated and used in the local food system. However, nowadays these species survive as minor crops only. In South America, quinoa and cañahua were cropped since the Inca era by the Tiahuanacu and Chiripa cultures (Juengst et al. 2016; Fritz et al. 2017; Bruno 2014).

Quinoa and cañahua are used as staple foods in rural and urban diets (Jacobsen et al. 2003; Penarrieta et al. 2008). The two cultivated Chenopods are halophytes, tolerating saline soils, resilient to low and high temperatures in dry, semi-arid to semi-desert lands (Choukr-Allah et al. 2016). It remains unclear whether cañahua must be considered a non-improved weedy, wild type of quinoa—a possibility attributable to the thickness of its testa—or a separate species entirely (Bruno and Whitehead 2003; Bruno 2006; Gade 1970). As quinoa was significantly boosted through the international year of the Quinoa in 2013 and as the ‘darling of celebrity’ for chefs and world hunger programmes, cañahua appears as the ‘Cinderella cousin’ (Fritz et al. 2017; Bjerga and Quigley 2014).

9.7 Tolerance to Abiotic Stresses

9.7.1 Drought Tolerance

Potato (*Solanum* spp.), quinoa, and cañahua are exposed to frequent drought and frost, and their yields vary considerably (Vacher 1998). In the Altiplano plateau, for more than 1 year in three, precipitation during the agricultural season is less than half the optimal for the crops (Vacher and Imaña 1987). Dizes and Bonifacio (1992) found that quinoa and cañahua can withstand drought, e.g. the cañahua has succulent leaves helping to adapt to low precipitation rates and arid conditions. Further, cañahua is known for growing in highland Altiplano communities with precipitation rates ranging between 250 and 600 mm year^{-1}. Under adverse climatic conditions of frequent droughts, night frost and on poor soils, cañahua persists in the Altiplano climate and has an enormous potential for export (Garcia et al. 2007, 2015).

9.7.2 Cold Tolerance

Cañahua seeds germinate even at low temperatures. We tested the germination of a Warikunca cultivar at six different temperatures and found that the temperature had a significant effect on the germination (Fig. 9.3a, b). Figure 9.3 shows the germination trends and reached according to our estimations the maximum germination of 98% at 3–14 °C (Rodriguez et al. 2016). At higher temperatures germination reached only 65% (Fig. 9.3b).

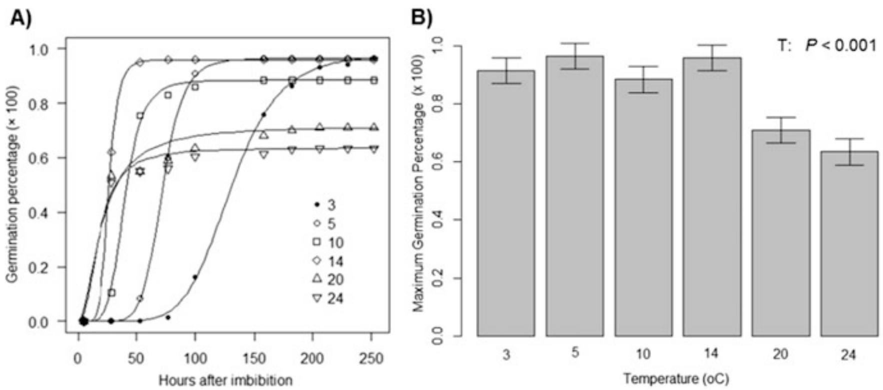

Fig. 9.3 Germination experiment with the cultivar Warikunca at the different temperature based on 50 seeds and four replicates. Germination curves (**a**) and maximum germination (**b**), error bars denote standard error (SE), *T* temperature levels (Rodriguez et al. 2016)

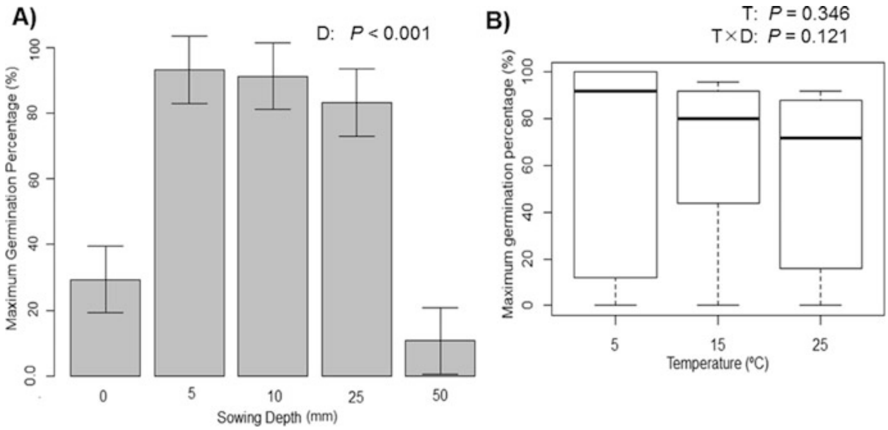

Fig. 9.4 Germination of cv. Warikunca at (**a**) five depths, and (**b**) at three temperature levels in mixed peat soil with fine sand, error bars denote to standard error (SE), $n = 4$, D sowing depth, T temperature (Rodriguez et al. 2016)

Estimated base temperature (T_b) was −0.9 °C like quinoa cultivars from the Southern and Central Altiplano of Bolivia (Bois et al. 2006). Quinoa sea level cv. Baer had 3 °C (Jacobsen and Bach 1998). *Amaranthus albus* L. and *A. palmeri* S. Watson have similar T_b close to 0 (Steinmaus et al. 2000), which confirms the ability of Chenopods to germinate at extreme temperature conditions.

Temperature and Sowing Depth Effects on Germination

Andean farmers in Bolivia and Peru grow cañahua under rainfed conditions. In an experiment with mixed fine sand and peat soil, sowing depth had significantly effect on seed germination (Fig. 9.4a). However, the temperature had no significant effect on the germination (Fig. 9.4b). At a sowing depth of 5–25 mm, the number of days the Warikunca cultivar needed to obtained 50% established plants (t_{50}), and maximum percentage of established plant was 18.3 and 19.6 days at 5 °C, (94–98%), respectively; 4.7 to 6.1 days at 15 °C (80–92%), and 1.8 to 2.2 days at 25 °C (76–90%) (Rodriguez et al. 2016).

There were no interactions between sowing depth and temperature (Fig. 9.4b). Sowing depths of 5 to 25 mm were appropriate and are recommended. In an experiment with cañahua genotypes (one landrace +5 cultivars), all germinated successfully. There were no significant differences between the two growth type (Saihua and Lasta), and no interaction between temperature, sowing depth and cañahua genotypes (Rodriguez et al. 2016).

In a similar experiment with *Amaranthus caudatus* L., *A. hypochondriacus* L. and *A. cruentus* L. Bavec and Mlakar (2002) obtained 80% emergence at 21 °C when sown at a depth of 5–15 mm. The same sowing depth is recommended for cañahua which has similar seed size.

The temperature did not affect the germination of cañahua significantly in the experiment depicted in Fig. 9.5. Eighty percent of the seeds germinated at 15 °C and at colder temperatures. Cañahua is sown in Bolivia and Peru between October and November when the temperatures are between 4 and 12 °C.

9.7.3 Salinity Tolerance

Cañahua can germinate under saline conditions (Koyro et al. 2011). Salinity problems in crop production are more frequent in places with a fast-growing human population and limited water resources, often resulting in the use of even poor-quality water for irrigation (Munns et al. 2002). In the Bolivian Altiplano, soils are many places affected by salinity due to high Na and K concentrations (Hervé et al. 2002). Cañahua can grow in loamy-clay soils with a pH of 4.8–8.5 and will tolerate saline soils S1 and S2 (4–8, 8–12 ds m^{-1}) (Vidaurre 2002; Hervé et al. 2002).

9.8 Production Aspects

9.8.1 Variety Selection

There are several cultivars obtained by selection and participatory plant breeding in Bolivia and Peru (Table 9.3). Classical breeding is difficult in cañahua due to the tiny flowers. All the cañahua cultivars were obtained by selection (Apaza 2010; Rojas et al. 2010; Mamani 2011). Participatory plant breeding (PPB) and participatory evaluation breeding (PEB) focusing gender participation have been carried out using the main selection criterion of seed yield and post-harvest use (Mamani 2011; Rojas et al. 2010; Rodriguez and Mamani 2016). However, many small-farmers in the rural communities are conserving cañahua landraces with low seed yields, but which are very resilient to adverse climatic events (Alanoca et al. 2008).

Participatory evaluations were developed from the Local Agricultural Research Committees (Comites de Investigación Agricola Local, CIAL). This initiative was developed by the International Center for Tropical Agriculture (CIAT) of Colombia at the beginning of 1990ies (Farnworth and Jiggins 2003). In 1994, PROINPA (Fundación para la Promoción e Investigación de Productos Andinos) started with a first pilot CIALs (Devaux et al. 2011). PROGRANO (Programa Granos Andinos, Facultad de Agronomia, UMSA) has applied the same methodology for improving cañahua in the Northern Altiplano of Bolivia (Mamani 2011).

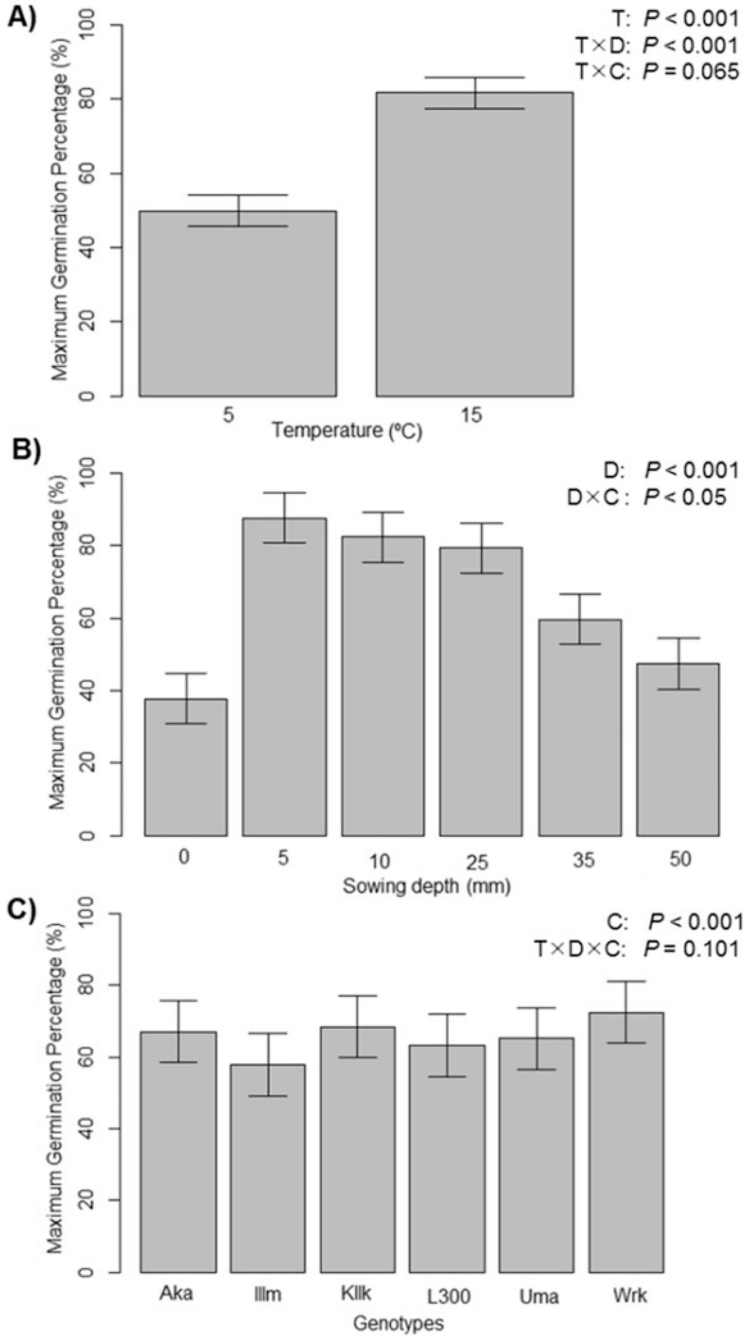

Fig. 9.5 Germination of cañahua genotypes at two temperatures and six sowing depths (**a**, **b**, and **c**) in a sandy loam soil, error bars denote standard error (SE), $n = 4$, *T* temperature, *D* sowing depth, *C* cañahua genotype (Rodriguez et al. 2016). Genotypes: Ak'apuya (Aka), Illimani (Ilm), Kullaca (Kllk), Line 300 (L300), Umacutama (Uma) and Warikunca (Wrk)

Table 9.3 Cañahua cultivars and landraces in Bolivia and Peru

Cultivar/landrace	Status	Plant type	Yield (kg ha^{-1})	Growth cycle (DAS)	Country
Umacutama	Landrace	Lasta	1320	140	Bolivia
Warikunca	Cultivar	Lasta	2100	145	Bolivia
Ak'apuya	Cultivar	Saihua	1600	130	Bolivia
Saihua Roja	Cultivar	Saihua	1430	150	Bolivia
Condornaira	Cultivar	Saihua	1300	140	Bolivia
Illimani	Cultivar	Lasta	800	160	Bolivia
Kullaka	Cultivar	Lasta	700	150	Bolivia
Lasta rosada	Cultivar	Lasta	1430	145	Bolivia
Lasta Naranja	Cultivar	Lasta	1100	153	Bolivia
Illpa INIA	Cultivar	Saihua	1410	150	Peru
Guinda canawa	Cultivar	Lasta	900	160	Peru
Huanacco	Cultivar	Lasta	750	160	Peru
Ayrampito	Cultivar	Lasta	na	160	Peru
Jacha Kahua	Cultivar	Lasta	na	160	Peru
Chuqui Chillihua	Cultivar	Lasta	na	140	Peru
Killu Cañawa	Cultivar	Lasta	na	160	Peru
Pacco Chilihua	Cultivar	Lasta	na	150	Peru
Waripunchu	Cultivar	Lasta	na	150	Peru

Source: Quispe (2004), Mamani (2011), Rojas et al. (2010), Estaña and Muñoz (2012)

9.8.2 Bio-fertilization

Cañahua does not demand fertilizer to produce an acceptable amount of seeds as other Chenopod species do, and it does not require particular attention during the growing season. This is a great advantage as the Andean farmers are unable to buy large amounts of fertilizers. Cañahua is usually sown after potatoes or fallow land. Production of cañahua is carried out according to traditional organic farming practices. INIA-Puno of Peru recommended applying 4–6 t ha^{-1} of sheep manure. Previously a soil analysis is recommended to estimate the appropriate amount of fertilizer. Usually, animal manure is manually applied in the row before sowing. Cañahua can produce 2.4 t seeds ha^{-1} if 120 kg N and 60 kg ha^{-1} P_2O_5 are applied (Apaza 2010). Soil tillage should be undertaken carefully, soil structure should be fine, because cañahua seeds are tiny (1–1.1 mm), and soil flattening is necessary. Excess water during the first stages of the plant establishment can cause loss of seedlings. Generally, cañahua is not fertilized, when it is sown after a potato crop. The mineralization of the potato debris results in an acceptable amount of nutrients for the cañahua crop.

Nevertheless, the organic fertilizer as sheep manure can release about 80 kg N ha^{-1} and 40 kg P ha^{-1}. Choque (2005) applied a rate of 10 t ha^{-1} of llama manure to the cv. Saihua Roja and harvested 2158 kg seeds ha^{-1}. Ticona (2011) used organic fertilizer (cow manure) under rainfed conditions, which economically and agronomically, increased seed yield in two cañahua cultivars (Lasta Rosada and Saihua

Amarilla) to 2677 and 2495 kg ha^{-1}. Meanwhile, Ramirez (2014) demonstrated as well that the use of organic fertilizer in a cropping system under drip irrigation increased seed yield to 2229 kg ha^{-1} in Lasta Naranja cañahua (Ramirez 2014). Lasta Naranja cultivar responded well to irrigation with seed yield of 2.3 t ha^{-1}. Ferti-irrigation applied in the ramification and branching stage could reduce the length of the growth period (113 DAS) compared to rainfed cultivation without fertilizer (152 DAS) (Ramirez 2014). It is advised that organic fertilizer should be applied in the morning for cultivating cañahua to avoid the effect of solar radiation on the microorganisms (Ramirez 2014).

The cañahua cv. Illpa INIA 406 (Saihua ecotype) performed very well in sandy loam soil (EC 0.62 ds m^{-1}) with a drip irrigation system (4500 m^3 ha^{-1}water applied during the growing season) in Majes rural community of Arequipa in Peru. This cultivar yielded 1410 kg ha^{-1} seed as the best with 20 tons ha^{-1} of poultry manure added resulting in a high economic benefit of 65.31% (Marquez 2015). The soils in the Bolivian and Peruvian Altiplano often have a low content of organic matter. Callisaya (2015) compared the production of cañahua (cv. Saihua Verde) in two soil types. The treatments consisted of plots with soil from the Northern Altiplano of Bolivia and plots with added peat. The seed yield was higher (851 kg ha^{-1}) in plots with the local soil without peat.

9.8.3 Crop Management

Sowing in Bolivia and Peru is carried out in spring (southern hemisphere) in September and November. Farmers in Bolivia and Peru broadcast the seeds in the field after land preparation has been done with oxen. Seeds are sown in rows with 40–50 cm. The sowing density is usually 4–5 kg ha^{-1} to get an adequate density of plants. When the plants are established in rows, the weeding is easily done. Cañahua is a robust crop. No pests and diseases are reported that can affect the development and growth significantly. However, mildew [*Peronosphora farinosa* (Fr.) Fr. (1849)] from neighbour quinoa plots can perturb before flowering (Tapia and Fries 2007).

9.8.4 Maturity and Harvest

When the crop matures and becomes ready to harvest, there is a risk of yield loss due to seed shattering. The tendency to shatter seed varies between localities due to different climate conditions (wind, hail, heavy rainfall) and plant growth types (Rodriguez et al. 2017). The plants flower over a long period. During flowering and physiological maturity (PM), seed shattering can be high. At this stage of development, the plants change colour, and the colour varies between cultivars or landrace. Serrano (2012) reported that the wild cañahua type 'pampalasta' did not shatter seeds. This wild type can be an interesting material for breeding new cañahua cultivars with less seed shattering. Recently, Paucara (2016) has compared 15 mutant cañahua cultivars obtained by radiation with a cañahua line type Lasta Rosada in the Experimental Station of Quipaquipani (Northern Altiplano, Bolivia). The cañahua mutant cultivars produced a seed yield of 1487 and 1109 kg ha^{-1}, and the Lasta Rosada cultivar produced 1649 kg ha^{-1}. The mutant cultivar had a short growth period of 110 DAS, in contrast to the non-mutant with 138 DAS. Albeit this comparison is promising, the seed shattering was between 10–20% (110.8 and 218.5 kg ha^{-1}). After cañahua reach physiological maturity, the plants are usually cut with a sickle in the early morning. Then the harvested plants are placed on carpets or tarpaulins and left outdoor until the plants' senescence.

9.9 Alternative Uses of Cañahua

9.9.1 Human Food Consumption

Cañahua seeds are commonly toasted and made into flour locally known in Peru as "caniahuaco" and as "pito" in Bolivia. It is eaten as a breakfast food, combined with wheat flour in baked products (Repo-Carrasco 2011; Repo-Carrasco et al. 2019) or used in cold and hot drinks (Peñarrieta et al. 2008; Quispe 2015). Toasted cañahua has become popular for rural and urban migrants in the cities, for instance, as an instant beverage (Churata 2015). *Pito* has a protein content of 13% and a high antioxidant activity (Fletcher 2016). The flour of cañahua has been combined with other Andean grains as amaranth and quinoa for children food (5–9 years old). The food products consisted of cookies, cereals and flour (semolina), with a final cost of USD 0.08100 g^{-1} (Delgadillo 2012).

9.9.2 Animal Feed

Grain hull, husk and by-products from the cañahua can be used to feed animals. There are three uses: (1) seeds are consumed as flour or toasted seeds or incorporated into feed products, (2) in Bolivia the cañahua sprouts are replacing green forage during the winter season to feed guinea pigs [*Cavia porcellus* (Linnaeus, 1758)], and (3) cañahua hull is used in guinea pigs feed. The lowest production cost was obtained with cañahua feed (USD 0.58/guinea pig), while a combination of cañahua and soybean (*Glycine max* (L.) Merr.) feed costed USD 0.80/guinea pig. Normal feed based on common wheat (*Triticum aestivum* L.) and soybean resulted in a cost of USD 0.61 (Calle 2004). Cortez (2016) has demonstrated good results in weight gain and growth in guinea pigs using cañahua husk with yellow maize, soybean cake, wheat husk, and straw. Cañahua by-products are more feasible compared to quinoa crop residues feed to guinea pigs. Aduviri (2006) recommended using 30% dry quinoa residue as a substitution for a diet based on the wheat meal. Feeding with by-products, hull and cañahua sprouts is an extraordinary alternative for rural livelihoods in marginal communities where nutritional feed sources are lacking.

9.10 Conclusions

Cañahua is an underutilized crop species with a potential to produce high value seeds in low input cropping systems under extreme conditions. Due to its wide diversity, cañahua tolerates both frost and high temperatures and is drought tolerant. Seeds can be used for human consumption as a protein crop replacing meat, combatting obesity, due to its high protein quality and high content of minerals like iron, vitamins and antioxidants. It is one of the crops for the future. Cañahua has a potential to be grown at larger scale on arid areas in the Andes and possibly other locations outside.

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References

ABI (2017) Cañahua de Oruro llega a la NASA. La Prensa (Digital), 8 de Mayo de 2017. http://www.laprensa.com.bo/economia/20170508/canahua-oruro-llega-la-nasa. Accessed 8 May 2017

Aduviri G (2006) Aplicacion de diferentes niveles de subproductos del beneficiado de quinua (*Chenopodium quinoa Willd.*) en la preparacion de raciones para cuyers (*Cavia porcellus* L.) en crecimiento y engorde. Facultad de Agronomía, UMSA, La Paz, Bolivia

Alandia G, Rodriguez JP, Jacobsen S-E, Bazile D, Condori B (2016) A new face of quinoa production: challenges for the Andean region. In: Quinoa for Future Food and Nutrition Security in Marginal Environments, Dubai, United Arab Emirates, 2016-12-06/2016-12-08 2016. ICBA, public, pp 29–30

Alanoca C, Flores J, Mamani E, Pinto M, Rojas W (2008) Preparación del terreno y siembra, Manejo tradicional del cultivo de cañahua. Serie No. 1. La Paz, Bolivia

Alvarez-Jubete L, Holse M, Hansen Å, Arendt EK, Gallagher E (2009) Impact of baking on vitamin E content of pseudocereals amaranth, quinoa, and buckwheat. Cereal Chem 86:511–515. https://doi.org/10.1094/CCHEM-86-5-0511

Apaza V (2010) Manejo y mejoramiento de kañiwa. Convenio Instituto Nacional de Innovacion Agraria INIA-Puno, Centro de Investigación de Recursos Naturales y Medio Ambiente-CIRNMA, Bioversity International y el International Fund for Agricultural Development-IFAD, Puno, Perú

Aro JM, Repo-Carrasco R, Calsin M (2017) Elaboracion de una mezcla alimenticia a base de quinua (*Chenopodium quinoa* Willd.), canihua (*Chenopodium pallidicaule* Aellen), cebada (*Hordeum vulgare* L.), maiz (*Zea mays* L.), haba (*Vicia faba* L.) y soya (*Glycine max* L. Merr.) por proceso de coccion-extrusion. Paper presented at the 6to Congreso Mundial de la Quinua, 3er Simposio Internacional de Granos Andinos, Puno, Peru, 2017-03-21/2017-03-24

Bavec F, Mlakar SG (2002) Effects of soil and climatic conditions on emergence of grain amaranths. Eur J Agron 17:93–103

Bjerga A, Quigley J (2014) Andean superfood lost in quinoa craze as orphan crop. http://www.bloomberg.com/news/2014-05-30/andean-superfood-lost-in-quinoa-craze-as-orphan-crop.html. Accessed 2 June 2014

Bois JF, Winkel T, Lhomme JP, Raffaillac JP, Rocheteau A (2006) Response of some Andean cultivars of quinoa (*Chenopodium quinoa* Willd.) to temperature: effects on germination, phenology, growth and freezing. Eur J Agron 25:299–308

Bravo R, Valdivia R, Andrade K, Padulosi S, Jäger M (2010) Granos andinos: avances, logros y experiencias desarrolladas en quinua, cañihua y kiwicha en Perú. Bioversity International, Roma

Brown AHD, Hodgkin T (2015) Indicators of genetic diversity, genetic erosion, and genetic vulnerability for plant genetic resources. In: Ahuja MR, Jain SM (eds) Genetic diversity and erosion in plants: indicators and prevention. Springer International Publishing, Cham, pp 25–53. https://doi.org/10.1007/978-3-319-25637-5_2

Bruno MC (2006) A morphological approach to documenting the domestication of *Chenopodium* in the Andes. In: Zeder MA, Bradley DG, Emshwiller E, Smith BD (eds) Documenting domestication: new genetic and archaeological paradigms. University of California Press, California, pp 32–45

Bruno MC (2014) Beyond raised fields: exploring farming practices and processes of agricultural change in the ancient Lake Titicaca Basin of the Andes. Am Anthropol 116(1):130–145. https://doi.org/10.1111/aman.12066

Bruno MC, Whitehead WT (2003) *Chenopodium* cultivation and formative period agriculture at Chiripa, Bolivia. Lat Am Antiq 14(3):339–355. https://doi.org/10.2307/3557565

Budin JT, Breene WM, Putnam DH (1996) Some compositional properties of seeds and oils of eight Amaranthus species. J Am Oil Chem Soc 73:475–481. https://doi.org/10.1007/BF02523922

Calle E (1980) Morfología y variabilidad de las cañahuas cultivadas (*Chenopodium pallidicaule* Aellen). Tesis Ing. Agr., Universidad Mayor de San Simon, Cochabamba, Bolivia

Calle E (2004) Efecto de la cañahua (*Chenopodium pallidicaule* Aellen), trito (*Triticum aestivum* L.), soya (*Glycine max* M.), germinados en la alimentacion de cuyes en recria para la prevencion de escorbuto. Thesis, Universidad Tecnica de Oruro, Oruro, Bolivia

Callisaya V (2015) Efecto de niveles de abonamiento con turba en el comportamiento de la qañawa (*Chenopodium pallidicaule* Aellen) bajo ambiente atemperado en K'iphakiphani-Viacha, Provincia Ingavi. Facultad de Agronomía, UMSA, La Paz

Carrasco E, Soto JL (2010) II. Importancia de los granos andinos. In: Rojas W, Soto JL, Pinto M, Jager M, Padulosi S (eds) Granos Andinos. Avances, Logros y Experiencias Desarrolladas en Quinua, Canahua y Amarnto en Bolivia. Bioversity International, Rome, pp 6–10

Catacora P (2017) El Centro de Conservacion de la Biodiversidad Genetica de la Quinua en Centro de Origen y Centro de Diversidad Genetica de la Region Andina. Paper presented at the 6to Congreso Mundial de la Quinua, 3er Simposio Internacional de Granos Andinos, Puno, 2017-03-21/2017-03-24

Choque R (2005). Efecto de niveles de fertilizacion con estiercol de llama (*Lama glama*) en tres ecotips de cañahua (*Chenopodium pallidicaule* Aellen) en el Altiplano Norte (Region Cordillera). Facultad de Agronomía, UMSA, La Paz

Choukr-Allah R, Rao NK, Hirich A, Shahid M, Alshankiti A, Toderich K, Gill S, Butt KUR (2016) Quinoa for marginal environments: toward future food and nutritional security in MENA and central Asia regions. Front Plant Sci 7:346. https://doi.org/10.3389/fpls.2016.00346

Churata P (2015) Elaboración de bebida instantanea de cañahua (*Chenopodium pallidicaule* Aellen) con actividad antioxidante. Tesis Lic. Quim. Ind., Universidad Mayor de San Andres, La Paz, 185p

Cortez H (2016) Evaluación de cuatro niveles de polvillo de Qañäwa (*Chenopodium pallidicaule* A.) en la alimentación de Cuyes (*Cavia porcellus* L.) en crecimiento. Revista Apthapi 1 (2):86–95

Cruz Torres E, Palomino Hasbach G, García Andrade JM, Mapes Sánchez C, González Jiménez J, Falcón Bárcenas T, Vázquez Arriaga O (2013) The genus *Chenopodium*: a potential food source. In: Jain SM, Dutta Gupta S (eds) Biotechnology of neglected and underutilized crops. Springer, Dordrecht, pp 3–31. https://doi.org/10.1007/978-94-007-5500-0_1

Delgadillo E (2012) Creation of three nutritional mixes based on amaranth (*Amaranthus caudatus*) and other Andean crops for school-aged childred (Cochabamba–Bolivia). All theses and dissertations paper 5356, 102p. http://scholarsarchive.byu.edu/etd

Devaux A, Ordinola M, Horton D (2011) Innovation for development: the Papa Andina experience. CIP, International Potato Center, Lima

Dizes J, Bonifacio A (1992) Estudio en microscopio electrónico de la morfología de los órganos de la quinua y de la canihua en relación con la resistencia a la sequía In: Actas de VII Congreso Internacional sobre Cultivos Andinos La Paz-Bolivia, p 5

Estaña W, Muñoz C (2012) Variabilidad Genetica de la Cañihua en las provincias de Puno. Equipo Tecnico del "Proyecto Mejoramiento de Capacidades Tecnico Productivas para la Competitividad de los Cultivos Andinos de Papa Nativa, Haba y Cañihua en la Region Puno", Puno

FAO (2017) The future of food and agriculture: trends and challenges. FAO, Food and Agriculture Organization of the United Nations, Rome

Farnworth CR, Jiggins J (2003) Participatory plant breeding and gender analysis. PPB Monograph No. 4. CIAT, Centro Internacional de Agricultura Tropical, Cali

Filomeno M (2017) Tras 6 años de auge, produccion de quinua bajo en 23% en 2016. Diario Pagina Siete. paginasiete.bo/economia/2017/1/9/tras-anos-auge-produccion-quinua-bajo-2016-123060.html. Accessed 16 Oct 2017

Fletcher RJ (2016) Pseudocereals: overview. In: Encyclopedia of food grains (2nd edn). Academic, Oxford, pp 274–279. doi:https://doi.org/10.1016/B978-0-12-394437-5.00039-5

Fritz GJ, Bruno MC, Langlie BS, Smith BD, Kistler L (2017) Cultigen chenopods in the Americas: a hemispherical perspective. In: Sayre MP, Bruno MC (eds) Social perspectives on ancient lives from paleoethnobotanical data. Springer International Publishing, Cham, pp 55–75. https://doi.org/10.1007/978-3-319-52849-6_3

Fuentes-Bazan S, Uotila P, Borsch T (2012) A novel phylogeny-based generic classification of *Chenopodium* sensu lato, and a tribal rearrangement of *Chenopodioideae (Chenopodiaceae)*. Willdenowia 42(June 2012):5–24

Gade DW (1970) Ethnobotany of cañihua (*Chenopodium-pallidicaule*), rustic seed crop of altiplano. Econ Bot 24(1):55–61. https://doi.org/10.1007/bf02860637

Gallego D, Russo L, Kerbab K, Landi M, Rastrelli L (2014) Chemical and nutritional characterization of *Chenopodium pallidicaule* (cañihua) and *Chenopodium quinoa* (quinoa) seeds. Emir J Food Agric 26(7):609–615. https://doi.org/10.9755/ejfa.v26i7.18187

Galluzzi G, López Noriega I (2014) Conservation and use of genetic resources of underutilized crops in the Americas—a continental analysis. Sustainability 6(2):980–1017

Galvez L, Apostolidis E, Genovese MI, Lajolo FM, Shetty K (2009) Evaluation of indigenous grains from the Peruvian Andean Region for antidiabetes and antihypertension potential using in vitro methods. J Med Food 12(4):704–713. https://doi.org/10.1089/jmf.2008.0122

Garcia M, Raes D, Jacobsen S-E, Michel T (2007) Agroclimatic constraints for rainfed agriculture in the Bolivian Altiplano. J Arid Environ 71(1):109–121. https://doi.org/10.1016/j.jaridenv.2007.02.005

Garcia M, Condori B, Castillo CD (2015) Agroecological and agronomic cultural practices of Quinoa in South America. In: Quinoa: improvement and sustainable production. Wiley, pp 25–46. https://doi.org/10.1002/9781118628041.ch3

Giuliani A, Hintermann F, Rojas W, Padulosi S (2012) Biodiversity of Andean Grains: balancing market potential and sustainable livelihoods. Bioversity International, Rome

Gorinstein S, Drzewiecki J, Delgado-Licon E, Pawelzik E, Ayala ALM, Medina OJ, Haruenkit R, Trakhtenberg S (2005) Relationship between dicotyledone-amaranth, quinoa, fagopyrum, soybean and monocots- sorghum and rice based on protein analyses and their use as substitution of each other. Eur Food Res Technol 221(1–2):69–77. https://doi.org/10.1007/s00217-005-1208-2

Gross R, Koch F, Malaga I, De Miranda AF, Schoeneberger H, Trugo LC (1989) Chemical composition and protein quality of some local Andean food sources. Food Chem 34 (1):25–34. https://doi.org/10.1016/0308-8146(89)90030-7

Hervé D, Ledezma R, Orsag V (2002) Limitantes y manejo de los suelos salinos y/o sódicos en el Altiplano Boliviano, CONDESAN–Consorcio para el Desarrollo Sostenible de la Ecorregion Andina, IRD—Institut de recherche pour le développement, La Paz, Junio 2002, 275p

Instituto Nacional de Estadisticas, INE (2018) Estadisticas economicas. Cuadros Estadisticos: Agricultura Instituto Nacional de Estadisticas (INE), Bolivia. https://wwwinegobbo/indexphp/estadisticaseconomicas/agropecuaria/agricultura/#1559000614062-ed9a91b8-2288. Accessed 20 July 2018

Jacobsen S-E (2003) The worldwide potential for Quinoa (*Chenopodium quinoa* Willd.). Food Rev Intl 19(1–2):167–177. https://doi.org/10.1081/FRI-120018883

Jacobsen S-E, Bach AP (1998) The influence of temperature on seed germination rate in quinoa (*Chenopodium quinoa* Willd.). Seed Sci Technol 26:515–523

Jacobsen S-E, Mujica A, Ortiz R (2003) The global potential for quinoa and other Andean crops. Food Rev Intl 19:139–148

Jacobsen S-E, Sørensen M, Pedersen S, Weiner J (2013) Feeding the world: genetically modified crops versus agricultural biodiversity. Agron Sustain Dev 33(4):651–662. https://doi.org/10.1007/s13593-013-0138-9

Jacobsen S-E, Sørensen M, Pedersen SM, Weiner J (2015) Using our agrobiodiversity: plant-based solutions to feed the world. Agron Sustain Dev 35(4):1217–1235. https://doi.org/10.1007/s13593-015-0325-y

Jarvis DE, Ho YS, Lightfoot DJ, Schmöckel SM et al (2017) The genome of *Chenopodium quinoa*. Nature 542(7641):307. https://doi.org/10.1038/nature21370

Jahaniaval F, Kakuda Y, Marcone MF (2000) Fatty acid and triacylglycerol compositions of seed oils of five Amaranthus accessions and their comparison to other oils. J Am Oil Chem Soc 77:847. https://doi.org/10.1007/s11746-000-0135-0

Juengst SL, Chávez SJ, Hutchinson DL, Chávez SR (2016) Late preceramic forager–herders from the Copacabana Peninsula in the Titicaca Basin of Bolivia: a bioarchaeological analysis. Int J Osteoarchaeol 27(3):430–440. https://doi.org/10.1002/oa.2566

Kent N (1983) Technology of cereals, 3rd edn. Pergamon Press, Oxford, New York

Khoury CK, Bjorkman AD, Dempewolf H, Ramirez-Villegas J, Guarino L, Jarvis A, Rieseberg LH, Struik PC (2014) Increasing homogeneity in global food supplies and the implications for food security. Proc Natl Acad Sci U S A 111(11):4001–4006. https://doi.org/10.1073/pnas.1313490111

Koyro H-W, Khan MA, Lieth H (2011) Halophytic crops: a resource for the future to reduce the water crisis? Emir J Food Agric 23(1):1–16

Langlie BAS, Hastorf CA, Bruno MC, Bermann M, Bonzani RM, Castellon WC (2011) Diversity in Andean *Chenopodium* domestication: describing a new morphological type from La Barca, Bolivia 1300–1250 B.C. J Ethnobiol 31(1):72–88. https://doi.org/10.2993/0278-0771-31.1.72

Lanza Lobo C (2017) Los nuevos indígenas urbanos comen chatarra. Diario Pagina Siete. http://www.paginasiete.bo/ideas/2017/2/26/nuevos-indigenas-urbanos-comen-chatarra-128481.html. Accessed 21 Oct 2017

Mamani F (2011) Estacion Experimental Choquenaira – Programa Granos Andinos. Paper presented at the Reunion Interna – IIAREN, 27 de Julio de 2011, Facultad de Agronomia, Universidad Mayor de San Andres

Mamani E (2013) Caracterizacion molecular de 26 accesiones de cañihua (*Chenopodium pallidicaule* Aellen) con mayor rendimiento en grano: Altiplano – Puno. Universidad Nacional del Altiplano. Escuela de Post Grado, Programa de Doctorado: Doctorado en Ciencia, Tecnologia y Medio Ambiente, Puno

Marquez J (2015) Tres abonos organicos en el cultivo de cañihua (*Chenopodium pallidicaule* Aellen) var. Illpa INIA 406 bajo riego por goteo en la irrigacion Majes-Arequipa. Thesis, Universidad Nacional de San Agustin de Arequipa, Arequipa

Maydana E (2010) Evaluacion de la produccion de seis variedades de cañahua (*Chenopodium pallidicaule* Aellen) con participacion de agricultores en la comunidad de Pacaure del Municipio de Mocomoco. Thesis, Universidad Mayor de San Andres, La Paz

Montealvo G, Solorza-Feria J, Velázquez del Valle M et al (2005) Composición química y caracterización calorimétrica de híbridos y variedades de maíz cultivadas en México. Revista Agrociencia 39(3):267–274

MINAGRI (2017) MINAGRI impulsa duplicar el consumo de granos andinos en los próximos cinco años. MINAGRI, Ministerio de Agricultura y Riego. http://www.minagri.gob.pe/portal/publicaciones-y-prensa/noticias-2017/19529-minagri-impulsa-duplicar-el-consumo-de-granos-andinos-en-los-proximos-cinco-anos. Accessed 25 Oct 2017

Ministerio de Salud-Bolivia (2017) En Bolivia se incrementa casos de Diabetes Mellitus y el Ministerio de Salud busca mejorar diagnóstico de la enfermedad. https://www.minsalud.gob.bo/2703-en-bolivia-se-incrementa-casos-de-diabetes-mellitus-y-elministerio-de-salud-busca-mejorar-diagnostico-de-la-enfermedad-2. Accessed 28 Oct 2017

Mundigler N (1998) Isolation and determination of starch from amaranth (*Amaranthus cruentus*) and quinoa (*Chenopodium quinoa*). Starch/Stärke 50(2–3):67–69. https://doi.org/10.1002/(SICI)1521-379X(199803)50:2/3<67::AID-STAR67>3.0.CO;2-R

Munns R, Husain S, Rivelli AR, James RA, Condon AG, Lindsay MP, Lagudah ES, Schachtman DP, Hare RA (2002) Avenues for increasing salt tolerance of crops, and the role of physiologically based selection traits. Plant Soil 247(1):93–105. https://doi.org/10.1023/a:1021119414799

Nascimento AC, Mota C, Coelho I, Gueifão S, Santos M, Matos AS, Gimenez A, Lobo M, Samman N, Castanheira I (2014) Characterization of nutrient profile of quinoa (*Chenopodium quinoa*), amaranth (*Amaranthus caudatus*), and purple corn (*Zea mays* L.) consumed in the north of Argentina: proximates, minerals and trace elements. Food Chem 148:420–426. https://doi.org/10.1016/j.foodchem.2013.09.155

Newton AC, Johnson SN, Gregory PJ (2011) Implications of climate change for diseases, crop yields and food security. Euphytica 179(1):3–18. https://doi.org/10.1007/s10681-011-0359-4

Paucara L (2016) Comportamiento agronomico de quince lineas de cañahua (*Chenopodium pallidicaule* Aellen), en la Estacion Experimental de Quipaquipani del departamento de La Paz. Facultad de Agronomía, Universidad Mayor de San Andres, La Paz

Peñarrieta JM, Alvarado JA, Akesson B, Bergenstahl B (2008) Total antioxidant capacity and content of flavonoids and other phenolic compounds in cañihua (*Chenopodium pallidicaule*): an Andean pseudocereal. Mol Nutr Food Res 52(6):708–717. https://doi.org/10.1002/mnfr.200700189

Quispe E (2004) Morfología y variabilidad de las cañahuas cultivadas (*Chenopodium pallidicaule* Aellen). Tesis Ing. Agr., Universidad Mayor de San Simon, Cochabamba

Quispe J (2015) Cañahua y amaranto, ayuda para diabéticos. La Razón (Edición Impresa), 7 de Agosto de 2015

Ramirez D (2014) Efecto de la aplicacion del fertirriego con la incorporacion de Biol-bovino en el cultivo de cañahua (*Chenopodium pallidicaule* Aellen) en la Estacion Experimental Choquenaira. Facultad de Agronomía, UMSA, La Paz

Rastrelli L, DeSimone F, Schettino O, Dini A (1996) Constituents of *Chenopodium pallidicaule* (Cañihua) seeds: isolation and characterization of new triterpene saponins. J Agric Food Chem 44(11):3528–3533. https://doi.org/10.1021/jf950253p

Repo-Carrasco R (2011) Andean indigenous food crops: nutritional value and bioactive compounds. University of Turku, Turku

Repo-Carrasco R, Espinoza C, Jacobsen SE (2003) Nutritional value and use of the Andean crops quinoa (*Chenopodium quinoa*) and kaniwa (*Chenopodium pallidicaule*). Food Rev Intl 19 (1–2):179–189. https://doi.org/10.1081/fri-120018884

Repo-Carrasco-Valencia R, Acevedo de La Cruz A, Icochea Alvarez JC, Kallio H (2009) Chemical and functional characterization of Kañiwa (*Chenopodium pallidicaule*) grain, extrudate and bran. Plant Foods Hum Nutr 64(2):94–101. https://doi.org/10.1007/s11130-009-0109-0

Repo-Carrasco-Valencia R, Hellstrom JK, Pihlava J-M, Mattila PH (2010) Flavonoids and other phenolic compounds in Andean indigenous grains: Quinoa (*Chenopodium quinoa*), kañiwa (*Chenopodium pallidicaule*) and kiwicha (*Amaranthus caudatus*). Food Chem 120(1):128–133. https://doi.org/10.1016/j.foodchem.2009.09.087

Repo-Carrasco-Valencia R, Melgarejo S, Pihlava JM (2019) Nutritional value and bioactive compounds in quinoa (*Chenopodium quinoa* Willd.), Kañiwa (*Chenopodium pallidicaule* Aellen) and Kiwicha (*Amaranthus caudatus* L.). Quinoa: cultivation, nutritional properties and effects on health

Rodriguez JP, Mamani F (2016) Participatory breeding and gender role in cañahua, a NUS Andean Grain crop in Bolivia. In: Gender, breeding and genomics – case studies, workshop held 18–21 October 2016, CGIAR Gender and Agriculture Research Network, Nairobi, p 5

Rodriguez JP, Jacobsen S-E, Sørensen M, Andreasen C (2016) Germination responses of Cañahua (*Chenopodium pallidicaule* Aellen) to temperature and sowing depth: a crop growing under extreme conditions. J Agron Crop Sci 202(6):542–553. https://doi.org/10.1111/jac.12158

Rodriguez JP, Aro M, Coarite M, Jacobsen S-E, Ørting B, Sørensen M, Andreasen C (2017) Seed shattering of Cañahua (*Chenopodium pallidicaule* Aellen). J Agron Crop Sci 203(3):254–267. https://doi.org/10.1111/jac.12192

Rojas W, Pinto M, Soto JL (2004) La erosion genetica de la cañahua LEISA. Revista de Agroecologia 20(1):35–36

Rojas W, Soto JL, Pinto M, Jäger M, Padulosi S (2010) Granos andinos: avances, logros y experiencias desarrolladas en quinua, cañahua y amaranto en Bolivia. Bioversity International, Roma

Serrano R (2012) Distribución de la diversidad genética y etnobotánica de cañahua (*Chenopodium pallidicaule* Aellen) en las comunidades del Altiplano Norte. Facultad de Agronomía, Universidad Mayor de San Andres, La Paz

Singh N, Singh P (2011) Amaranth: potential source for flour enrichment. In: Preedy VR, Watson RR, Pater VB (eds) Flour and breads and their fortification in health and disease prevention. Elsevier, p 102

Sistema Integrado de Estadistica Agraria, SIEA (2018) Anuario estadistico de produccion agropecuaria. Ministerio de Agricultura y Riego, Minagri, Peru. http://siea.minagri.gob.pe/siea/?q=publicaciones/anuario-de-produccion-agricola. Accessed 28 Sept 2018

Soto JL, Valdivia R, Solano OC (2017) Normas tecnicas Peruanas – Requisistos de calidad para granos Andinos. Paper presented at the 6to Congreso Mundial de la Quinua, 3er Simposio Internacional de Granos Andinos, Puno, 2017-03-21/2017-03-24

Spehar CR, Santos RLD (2002) Quinoa BRS Piabiru: alternative for diversification of cropping systems. Pesquisa Agropecuaria Brasileira 37(6):889–893. https://doi.org/10.1590/s0100-204x2002000600020

St.Clair SB, Lynch JP (2010) The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. Plant Soil 335(1):101–115. https://doi.org/10.1007/s11104-010-0328-z

Steinmaus S, Prather TS, Holt JS (2000) Estimation of base temperatures for nine weed species. J Exp Bot 51(343):275–286. https://doi.org/10.1093/jexbot/51.343.275

Tapia M (1997) Cultivos Andinos Subexplotados y su aporte a la alimentación. Oficina Regional de la FAO para America Latina y el Caribe, Santiago

Tapia ME, Fries AM (2007) Guía de campo de los cultivos andinos. FAO, ANPE-PERÚ. http://www.fao.org/3/ai185s/ai185s00.htm. Accessed 21 Sept 2018

Ticona JC (2011) Efecto de la Biofertilizacion en dos lineas de cañahua (*Chenopodium pallidicaule* Aellen), en Calasaya Provincia Los Andes. Facultad de Agronomía, Universidad Mayor de San Andres, La Paz

Vacher JJ (1998) Response 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. Agric Ecosyst Environ 68:99–108

Vacher JJ, Imaña E (1987) Los riesgos climaticos en el altiplano Boliviano. OMM-SENAMHI-ORSTOM, La Paz

Vidaurre R (2002) Determinación de la epoca optima de cosecha en tres cultivares de saihua de cañahua (*Chenopodium pallidicaule* Aellen). Facultad de Agronomía, UMSA, La Paz

Villena JE (2016) Epidemiologia de la diabetes Mellitus en el Peru. Diagnostico 55(4) Octubre – Diciembre, pp 173–181

World Health Organization (2016) Global report on diabetes, Switzerland, 88p. http://apps.who.int/iris/bitstream/10665/204871/1/9789241565257_eng.pdf?ua=1

Chapter 10
Response of *Amaranthus* sp. to Salinity Stress: A Review

Atul Bhargava and Shilpi Srivastava

Abstract Salinity is one of the world's most pressing environmental problems that has affected nearly one-third of the world's cultivated land. Ionic toxicity, osmotic stress, and nutritional defects under severe salt stress may lead to metabolic imbalances and resultant oxidative stress. *Amaranthus* spp. have been cultivated for centuries as a grain and foliage crop in many parts of the world due to the high nutritional value of its leaves and seeds as well as its resistance against both biotic and abiotic stresses like heat, drought, diseases, and pests. Many species of the genus have been reported to tolerate adverse environmental stresses which have been associated with their C_4 physiology, indeterminate flowering habit, long tap root system, extensive lateral root system, accumulation of compatible solutes, efficient water usage, and the expression of stress-related genes and transcription factors. This chapter presents an updated account of the various reports available with respect to salinity stress in this underutilized crop.

Keywords *Amaranthus* · Salinity stress · Germination · Enzyme expression · Transcription factors

10.1 Introduction

Abiotic stress refers to any environmental condition, apart from the action of other organisms, which has a detrimental effect on the growth, survival, and/or fecundity of plants (Boscaiu et al. 2008; Cramer et al. 2011). Therefore, any environmental factor that reduces production and limits plant biomass is termed as stress (Grime

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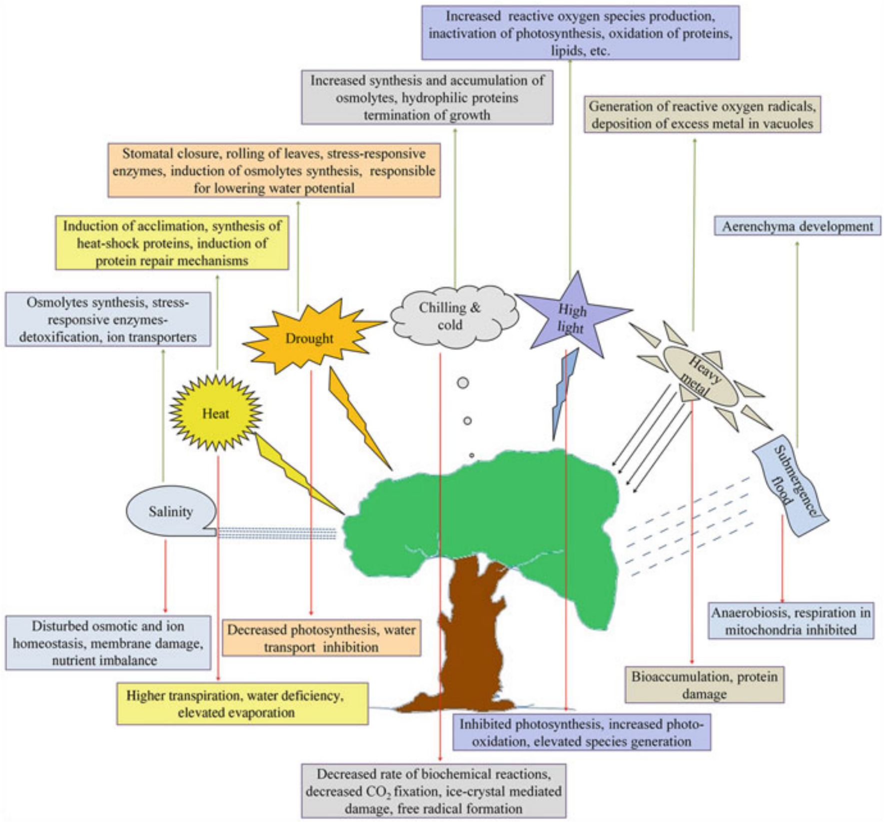

Fig. 10.1 Diverse abiotic stresses and the strategic defense mechanisms adopted by the plants (Meena et al. 2017)

1979; Robert-Seilaniantz et al. 2010). Abiotic environmental factors include parameters like temperature, moisture availability, salinity, acidity, light availability, submergence, anaerobiosis, mineral availability, frost, and CO_2, all of which determine the growth of a plant (Bhargava and Srivastava 2013). Abiotic stresses lead to reduced growth and yield and trigger a range of morphological, physiological, biochemical, and molecular changes in plants (Bhatnagar-Mathur et al. 2008). Plants have the unique ability to cope with the rapid fluctuations and adversity of environmental conditions due to their intrinsic metabolic capabilities (Fig. 10.1) (Simontacchi et al. 2015; Meena et al. 2017). The response of plants to stress can be either elastic (reversible) or plastic (irreversible), and is dependent on the tissue or organ affected by the stress (Cramer et al. 2011). If the stress becomes harsh or continues for a longer duration, it may lead to unbearable metabolic burden on cells leading to reduced growth that would ultimately lead to plant death.

Since human intervention in the ecosystem is continuously increasing which has resulted in a rapid deterioration of the environment, it is imperative to have a look at the plants that can tolerate and flourish in these abiotic stresses. Salinity is one such abiotic stress that severely limits the growth and fecundity of plants. Amaranths are known for their nutritional superiority and the ability to grow in stressful conditions. Therefore, the present work has been formulated to have greater insight in the salinity tolerance of *Amaranthus* spp.

10.2 Salinity Stress: An Overview

Salinity is one of the world's most pressing environmental problems that has affected nearly one-third of the world's cultivated land (Bhargava and Srivastava 2013; Stavridou et al. 2017). According to FAO (2010), more than 800 million ha of land was affected with salinity in 2008 that accounted for more than 6% of the world's total land area. The area under salinization is increasing day by day and was estimated to be 34 million of the total irrigated land around the world 2012. The National Academy of Sciences (USA) includes salinization of soil and water as one of the leading processes contributing to a possible worldwide catastrophe due to non-utilization of such lands (Francios and Mass 1994). Table 10.1 provides information on salinity, sodicity, and alkalinity prevalent in the soils and their effects on plant development. Saline and sodic soils are common in the arid and semi-arid lands and are characterized by an excess of inorganic salts occurring due to high rates of evapotranspiration and lack of water leaching (Mengel and Kirkby 1982; Shannon et al. 1994). In contrast to the humid regions where precipitation tends to leach affected soils, poor drainage in arid lands is the major cause of salinity in such areas as it prevents the salts from reaching their ultimate sink, the sea. Salinity is detrimental to plant growth in a variety of ways. The presence of large amount of salt in the soil makes absorption of water by the roots difficult leading to reduced growth rate (Munns and Tester 2008). This condition is commonly referred to as "osmotic or water-deficit effect" of salinity. Salt-specific or ion-excess effect of salinity occurs when massive amounts of salt gain entry into the plant in the transpiration channel leading to cell injury in the transpiring leaves causing further reductions in growth (Greenway and Munns 1980). In saline environments, the sodium and chloride ions penetrate the hydration shells of proteins and alter the non-covalent interactions

Table 10.1 Classification of saline, sodic and alkaline soils according to USDA salinity laboratory (USSL 2005)

Soil type	Details	Effect on plant growth
Saline	High concentration of soluble salts $EC_e \geq 4$ dS m^{-1}	Inhibition of shoot and root growth due to osmotic and salt specific components.
Alkaline	Low concentration of soluble salts, but a high exchangeable Na + percentage (ESP) $EC_e \geq 15$ dS m^{-1}	Inhibition of root growth due to poor soil structure
Alkalinity	Type of sodic soil with a high pH $EC_e \geq 15$ dS m^{-1}, pH 8.5–10	Nutrient uptake is affected due to high pH

between the amino acids causing change in conformation and loss of function of proteins (Chinnusamy and Zhu 2003). Ionic toxicity, osmotic stress, and nutritional imbalances under salt stress results in metabolic imbalances and resultant oxidative stress (Zhu 2001; Chinnusamy and Zhu 2003).

10.3 *Amaranthus*: A Potential New Crop

The family Amaranthaceae (order Caryophyllales), also known as the amaranth or pigweed family, contains about 165 genera and 2040 species mostly herbs and subshrubs having worldwide distribution. The taxonomic reorganization of Amaranthaceae is still in progress that leads to significant differences in the number of genera and species reported. Allen (1961) divided family Amaranthaceae into two sections mainly on the basis of taxonomical studies.

1. *Amaranthus* saucer ($x = 16$ and 17)
2. Blitopsis dumort ($x = 17$)

Thus the section *Amaranthus* is primarily dibasic along with polyploidy reported in *A. dubius* (Pal 1972; Pal and Khoshoo 1965; Madhusoodanan and Pal 1981).

Amaranthus species are known for their nutritional superiority and their resistance to abiotic stresses like heat, drought, diseases, and pests (NRC 1984; Tucker 1986; Bhargava et al. 2003, 2004; Shukla et al. 2006, 2010). Besides its immense nutraceutical importance, several members of the genus can also be grown successfully in varied soils and agro-climatic conditions (Katiyar et al. 2000; Shukla and Singh 2000). About 400 species of *Amaranthus* have been reported to be distributed throughout the world in temperate, subtropical, and tropical climate zones (Suma et al. 2002). The species have been subdivided mainly on the basis of their utilization method, viz., grain amaranth (*A. hypochondriacus*, *A. cruentus*, *A caudatus*, and *A. edulis*), vegetable amaranth (*A. tricolor* and *A. lividus*), ornamental amaranth (*A. tricolor*), and weedy amaranth (*A. hybridus*, *A. powellii*, and *A. quitensis*) (Sauer 1967; Pal and Khoshoo 1972, 1974; Madhusoodanan and Pal 1981) (Table 10.2). The genus was domesticated around 8000 years ago by the people of the Aztec and the Mayan civilization of South and Central America and spread throughout Europe by the 1700s (Sauer 1967). By the twentieth century, it had spread throughout the world and grew in China, India, Africa, and Europe, as well as in North and South America (Rastogi and Shukla 2013).

10.4 *Amaranthus* and Salt Stress

Amaranthus spp. are known to tolerate adverse abiotic stresses which have been associated with a long tap root system and an extensive lateral root system, C_4 physiology, indeterminate flowering habit, superior water use efficiency, accumulation of compatible solutes, and the expression of stress-related genes and transcription factors (Kauffman and Weber 1990; Johnson and Henderson 2002; Omamt et al. 2006; Huerta-Ocampo et al. 2009, 2011, 2014; Aguilar-Hernandez et al. 2011; Castrillón-Arbeláez and Frier 2016). With respect to salt stress, it was as early as 1992 that Amaranthaceae was reported to be one of the three families of higher plants which have a sodium requirement for growth (Murata et al. 1992).

10.5 Salt Stress in *Amaranthus*: Germination and Morphological Parameters

Jamil et al. (2006) evaluated the effect of salt stress on germination and early seedling growth in *Amaranthus paniculatus* and also assessed the relationship between salinity stress and growth. The NaCl solutions used for the study had the electrical conductivities (ECs) of 4.7, 9.4, and 14.1 dS m^{-1}. It was observed that the germination of the amaranth was strongly affected by the salt treatment as the higher salt concentration leads to lower seed sprouting. Salt stress was detrimental to seedling growth and led to reduced biomass of both root and shoot. The root length was more affected as compared to the shoot length.

Salt stress experiments were performed in *A. tricolor* using salt solutions at electrical conductivity (EC) levels of 1, 2, 4, and 8 dS m^{-1} by Ribeiro and Combrink (2006). Morphological parameters along with leaf calcium and protein contents were investigated in detail. Two studies were undertaken in the abovementioned experiment using *A. tricolor*. The first study comprised of harvesting at 30 and 45 days after transplanting (DAT). In the second study, two cutting heights, viz., topping at 25% and 50% of plant height were used at 3 stages viz. 25, 35, and 45 DAT. The plants adapted in course to time to saline conditions were evident from the fact that the optimum EC level for a high shoot: root ratio was 4 dS m^{-1} 30 DAT compared to 8 dS m^{-1} 45 DAT. The EC value of 4 dS m^{-1} yielded highest leaf mass for both harvesting heights, but at 8 dS m^{-1} lower cutting height produced significantly higher yields as compared to 50% cutting height, which showed that *A. tricolor* can rapidly adapt to saline conditions (Ribeiro and Combrink 2006). Increased EC levels improved the nutrient contents of this leafy vegetable by enhancing the leaf protein content.

Omamt et al. (2006) analyzed the response of amaranth germplasm belonging to *A. tricolor*, *A. hypochondriacus* and *A. cruentus* in a greenhouse to salt stress. Parameters like gas exchange, water use, and leaf anatomical changes were studied. Saline water at 0, 25, 50, 100, and 200 mM sodium chloride, equivalent to electrical conductivities of 1.2, 4.1, 7.0, 12.8, and 24 dS m^{-1}, respectively, was taken for the study. Salinity stress led to inhibition of plant growth, photosynthetic rate, and stomatal conductance in all four amaranth genotypes. Photosynthetic rate and stomatal conductance were significantly reduced by salt stress. There was reduction in shoot growth which was greater at 50 and 100 mM NaCl in *A. tricolor* than in

Table 10.2 List of various species with their local name of Genus *Amaranthus* (modified from Rastogi and Shukla 2013)

S. No.	Name of species	Vernacular name
1.	*Amaranthus gangeticus* is a synonym of *Amaranthus tricolor* L.	Elephant head amaranth
2.	*Amaranthus floridanus* (S. Watson) Sauer	Florida amaranth
3.	*Amaranthus graecizans* L.	–
4.	*Amaranthus fimbriatus* (Torr.) Benth.	Fringed amaranth, fringed pigweed
5.	*Amaranthus dubius* Mart. ex Thell	Spleen amaranth, khada sag
6.	*Amaranthus deflexus* L.	Large-fruit amaranth
7.	*Amaranthus cruentus* L.	Purple amaranth, red amaranth, Mexican grain amaranth, huauhtli
8.	*Amaranthus crispus* (Lesp. & Thévenau) A. Terracc.	Crisp leaf amaranth
9.	*Amaranthus crassipes* Schltdl.	Spreading amaranth
10.	*Amaranthus chlorostachys* Willd.	Chihuahuan amaranth
11.	*Amaranthus chihuahuensis* S. Watson	–
12.	*Amaranthus caudatus* L.	Love lies-bleeding, pendant amaranth, tassel flower, quilete, amaranto, kiwicha, millmi
13.	*Amaranthus cannabinus* (L.) Sauer	Tidal-marsh amaranth
14.	*Amaranthus californicus* (Moq.) S. Watson	California amaranth, California pigweed
15.	*Amaranthus brownii* Christoph. & Caum	Brown’s amaranth
16.	*Amaranthus blitum* L.	Purple amaranth
17.	*Amaranthus blitoides* S. Watson	Mat amaranth, prostrate amaranth, prostrate pigweed
18.	*Amaranthus bigelovii* U. & B.	Bigelow’s amaranth
19.	*Amaranthus australis* (A.Gray) Sauer	Southern amaranth
20.	*Amaranthus acanthochiton Sauer*	Greenstripe
21.	*Amaranthus acutilobius*	Sharp-lobe amaranth
22.	*Amaranthus albus* L.	White pigweed, prostrate pigweed, pigweed amaranth
23.	*Amaranthus arenicola I.M.Johnst.*	Sandhill amaranth
24.	*Amaranthus torreyi* (A. Gray) Benth. ex S. Watson	Torrey’s amaranth
25.	*Amaranthus thunbergii* Moq.	Thunberg’s amaranth
26.	*Amaranthus standleyanus* Parodi ex Covas	–
27.	*Amaranthus spinosus* L.	Spiny amaranth, prickly amaranth, thorny amaranth
28.	*Amaranthus scleropoides* Uline & W.L. Bray	Bone-bract amaranth
29.	*Amaranthus rudis* J.D. Sauer	Tall amaranth, common water hemp
30.	*Amaranthus retroflexus* L.	Red-root amaranth, redroot pigweed, common amaranth
31.	*Amaranthus quitensis* Kunth is a synonym of *Amaranthus hybridus* subsp. *quitensis* (Kunth) Costea & Carretero	Ataco, sangorache, amaranto negro

(continued)

Table 10.2 (continued)

S. No.	Name of species	Vernacular name
32.	*Amaranthus pumilus* Raf.	Seaside amaranth
33.	*Amaranthus pringlei* S. Watson	Pringle's amaranth
34.	*Amaranthus viridis* L.	Slender amaranth, green amaranth
35.	*Amaranthus watsonii* Standl.	Watson's amaranth
36.	*Amaranthus wrightii* S. Watson	Wright's amaranth
37.	*Amaranthus tuberculatus* (Moq.) Sauer	Rough-fruit amaranth, tall waterhemp
38.	*Amaranthus tricolor* L.	Joseph's-coat
39.	*Amaranthus lineatus* R.Br.	Australian amaranth
40.	*Amaranthus leucocarpus* S. Watson	–
41.	*Amaranthus hypochondriacus* L.	Prince-of-Wales-feather, princess feather, quelite, blero
42.	*Amaranthus hybridus* L.	Smooth amaranth, smooth pigweed, red amaranth
43.	*Amaranthus greggii* S. Watson	Gregg's amaranth
44.	*Amaranthus powelii* S. Watson	Green amaranth, Powell amaranth, Powell pigweed
45.	*Amaranthus polygonoides* L.	Tropical amaranth
46.	*Amaranthus paniculatus* L.	Reuzen amarant
47.	*Amaranthus palmeri* S. Watson	Palmer's amaranth, palmer pigweed, careless weed
48.	*Amaranthus obcordatus* (A. Gray) Standl.	Trans-Pecos amaranth
49.	*Amaranthus muricatus* (Gillies ex Moq.) Hieron.	African amaranth
50.	*Amaranthus minimus* Standl.	–
51.	*Amaranthus mantegazzianus* Pass. is a synonym of *Amaranthus caudatus* L.	Quinoa de Castilla
52	*Amaranthus lividus* L. is a synonym of *Amaranthus blitum* subsp. *oleraceus* (L.) *Costea*	–

A. hypochondriacus and *A. cruentus.* At 100 mM NaCl, the water-use efficiency ranged from 3.9 g in *A. tricolor* to 6.7 g dry mass kg^{-1} H_2O in *A cruentus*. Specific leaf area (SLA) decreased with salinity and showed variation between genotypes. The amaranth germplasm exhibited significant negative association between SLA and water-use efficiency. As compared to *A. hypochondriacus and A. cruentus*, *A. tricolor* exhibited thin leaves, more stomata, and larger stomatal apertures.

Bialecka and Kepczynski (2009) investigated the effects of different doses of two plant regulators, viz., Ethephon and gibberellin A3 (GA3) during salinity stress on seed germination and amylase activity in the seeds of *A. caudatus*, a type of ornamental amaranth. While the salt concentration of 25 and 50 mM delayed germination, 50%, 90%, and 99.5% inhibition was observed at 75, 100, and 125 mM. Both ethephon and GA3 promoted seed germination under salt stress with the seeds showing more sensitivity to ethephon as compared to GA3. The results clearly showed the inhibitory effect of sodium chloride on *A. caudatus* seed germination.

The effects of salt stress on the germination characteristics of amaranth (*Amaranthus mangostanus*) seeds were investigated by Luo and Sun (2012). Data was recorded for germination rate, taproot length, and length of hypocotyledonary axis for NaCl concentrations of 30, 60, 90 and 120 mmol L^{-1}. The germination rate, germination potential, taproot length, and length of hypocotyledonary axis increased at 30 mmol L^{-1} NaCl concentrations but then decreased with an increase in the concentration of NaCl. The authors concluded that the lower NaCl concentrations promoted seed germination, while higher concentrations inhibited the phenomenon in amaranth.

Odjegba and Chukwunwike (2012) evaluated the physiological responses of *Amaranthus hybridus* at 0, 0.1 and 0.2 M sodium chloride for 6 weeks. The dry weight of plants that did not receive salt treatment was 11.67 g, while those receiving 0.1 and 0.2 M salt solution had a dry weight of 9.22 and 6.94 g, respectively. The control plants had relative water content (RWC) value of 74%, which was significantly higher than the RWC calculated for 0.1 and 0.2 M salt treatments. The decrease in RWC during salt stress might have been due to enhancement in the osmotic pressure of the external solution created by high salt concentration that led to a reduction in the water potential which in turn negatively influenced the water uptake by plant roots (Odjegba and Chukwunwike 2012). It was also observed that salinity significantly decreased the dry weight of the plant and the effect increased with salt concentration.

The salt resistance level of six amaranth cultivars was evaluated at the germination stage for five NaCl concentrations by Wouyou et al. (2016). It was observed that salinity stress was inhibitory to seed germination and led to reduced germination index in all cultivars with the delay in seed germination rate proportional to the NaCl concentration. The average reduction due to NaCl stress was 22.11%, 20.90%, 17.28%, 15.58%, 8.03%, and 6.57% for the cultivars AA-04-017, AA-04-028, Rouge, Locale, Stem2-Sat2 and Red-Sudan, respectively. It was observed that the cultivars of *Amaranthus cruentus exhibited genetic* variability for salinity-stress resistance at the germination stage (Wouyou et al. 2016).

Hao et al. (2017) determined the effects of salt stress on germination response by treating the seeds of *A. retroflexus*, *A. spinosus*, *A. viridis*, and *A. blitum* with 25, 50, 100, 150, and 200 mM NaCl solution (Fig. 10.2). It was observed that with the increase in salt concentration, maximum germination percentage (G_{max}) decreased and time for 50% germination increased, except in *A. retroflexus* and *A. blitum* both of which showed slight increase in G_{max} at 150 mM NaCl. Higher and quicker germinations response at all concentrations was observed in *A. retroflexus* and *A. blitum* as compared to *A. spinosus* and *A. viridis.*

Menezes et al. (2017) evaluated the effect of salinity stress (25, 50, 75 and 100 mM NaCl) on the growth parameters in *A. cruentus* L. ('BRS Alegria' cultivar). Salinity significantly reduced plant height, stem diameter, leaf area, dry mass yield, and relative water content indicating that the amaranth cultivar is sensitive to salt stress. The sodium and chloride levels in different plant parts increased linearly with

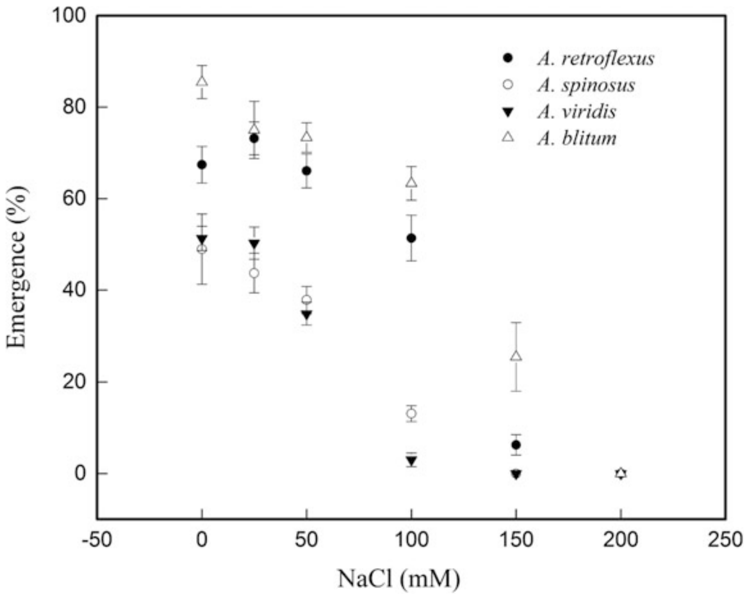

Fig. 10.2 The effect of NaCl on germination response of four *Amaranthus* species fitted to three-parameter sigmoid model (Hao et al. 2017)

an increase in NaCl concentration as also reported by da Costa et al. (2008) while working on *Amaranthus* spp. wherein an increase of the saline concentration in the irrigation water reduced N, K^+, and Mg^{2+} levels in the roots and increased the levels of Cl^- in the stem and Na^+ in the different parts of the plants.

10.6 Salt Stress in *Amaranthus*: Biochemical Studies

Gaikwad and Chavan (1995, 1999) reported that increasing the salinity of the irrigation water from 4 to 6 dS m^{-1} reduced plant carbohydrates, oxalates, and nitrates at both vegetative and flowering stages in three amaranth species (*A. caudatus*, *A. hypochondriacus*, and *A. paniculatus*). Moreover, when the salinity of irrigation water was increased to 16 dS m^{-1}, there was a marked decrease in leaf transpiration, diffusive resistance to CO_2, and more negative osmotic potential in *A. caudatus*, *A. hypochondriacus*, and *A. paniculatus* (Gaikwad and Chavan 1998).

Wang et al. (1999) examined the photosynthetic adaptation mechanisms for salinity stress in *A. tricolor* with reference to the buildup of glycine betaine that are known osmoprotectants. The light harvesting complex II (LHCII), photosystem I (PSI), and photosystem II (PSII) were significantly lower in non-green regions of the leaf. In contrast, the contents of other photosynthetic proteins were comparatively high. The red and yellow regions exhibited 40% net photosynthetic CO_2 fixation activity as compared to the green parts. The administration of salt stress to the tune of 0.3 M NaCl for 5 days showed that the levels of chlorophyll, PSI, PSII, RuBisCO, and the CO_2 fixation rate in the green portion of the leaves decreased significantly, whereas those in the non-green regions were unaffected. The glycine betaine, betaine-aldehyde dehydrogenase, and choline monooxygenase content in the leaves increased on exposure to salinity stress. The abovementioned findings suggest that the low concentration of light harvesting pigments in the non-green portions of amaranth leaves is favorable during salt stress since the photosynthetic apparatus maintained its integrity and function even at high salt concentrations (Wang et al. 1999).

Wang and Nii (2000) investigated the effect of salinity stress on leaf growth, chlorophyll content, ribulose bisphosphate carboxylase oxygenase (RuBisCO), and glycine betaine (GB) with reference to photoassimilation and transpiration in response to salinity stress in the leaves of *A. tricolor*. Salt stress was induced by transferring the plants to growth media containing 300 mM sodium chloride for 7 days followed by growth in normal medium for 7 days. There was increase in the chlorophyll content possibly due to decrease in water content of the leaves. The RuBisCO and soluble protein initially showed reduction in response to salt stress but showed gradual increase when plants were grown in normal media. Glycine betaine content showed slight increase during the initial days of salt treatment that was possibly due to salinity stress. A sharp decrease in the GB content was noticed when the plants were transferred to normal medium, but the GB content stood at higher levels throughout the relief period. A decrease in photosynthesis and transpiration was observed prior to changes in leaf area, RuBisCO, or GB content. However, the photosynthetic rate and transpiration levels were gradually restored during the relief period in normal medium. The results led to an understanding that GB content was an important adaptation to salt stress in the species, although salt stress leads to significant changes in photosynthesis and transpiration rates.

Physiological parameters like proline content, superoxide dismutase (SOD) activity, and malondialdehyde (MDA) content were estimated in NaCl-treated amaranth plants (*Amaranthus mangostanus*) by Luo and Sun (2012). The MDA content was less affected under low NaCl (30–60 mmol L^{-1}) concentrations but significantly increased at high salt concentrations (90–120 mmol L^{-1}). Proline, which plays a crucial role in the osmotic adjustment of the plant under abiotic stresses, increased with increasing salinity. The SOD activity was also higher in treated plants as compared to the controls which suggested that the antioxidant defense system was rapidly enhanced to scavenge all reactive oxygen species (ROS) generated due to oxidative stress.

Odjegba and Chukwunwike (2012) evaluated the chlorophyll content, lipid peroxidation, protein content, and antioxidant activity in sodium chloride-treated *Amaranthus hybridus* plants. It was observed that salinity induced a significant reduction in the chlorophyll (Fig. 10.3a) and protein content (Fig. 10.3b) but enhanced malondialdehyde (MDA) content, catalase, and ascorbate peroxidase (APX) activity. The extent of changes in these parameters was dependent on the concentration of the salt used. The increase in MDA content and antioxidant

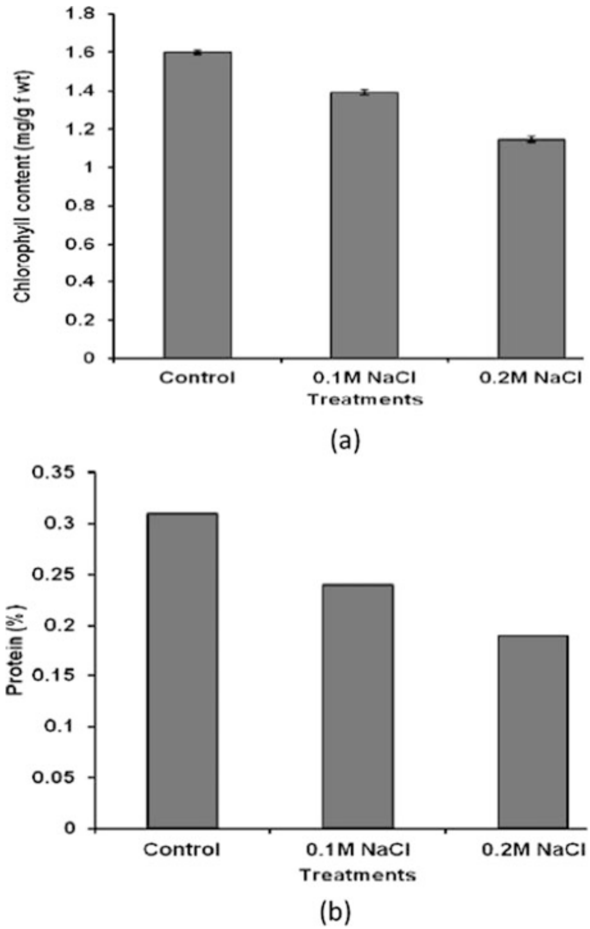

Fig. 10.3 Effect of different salt concentrations on *Amaranthus hybridus*. (**a**) Chlorophyll content (**b**) Protein content (Odjegba and Chukwunwike 2012)

enzymes activities indicates that though salinity stress induces the production of reactive oxygen species (ROS), a concomitant increase in the antioxidant enzymes helps mitigate the salt stress in living cells.

All types of abiotic stresses including salt stress are also known to affect vitamin concentration in food plants. The influence of varying concentrations of NaCl (20 mM, 40 mM, and 60 mM NaCl) on β-carotene, vitamin B1, vitamin B6, and ascorbic acid contents in the leaves of *Amaranthus polygamous* was estimated by Ratnakar and Rai (2013). The β-carotene and thiamine content in the leaves of *A. polygamous* showed a decrease with increasing concentration of NaCl. The riboflavin content showed a decrease of 20% at 20 mM NaCl, while around 23% decrease in riboflavin content was observed at 40 and 60 mM NaCl, respectively (0.035 mg 100 g^{-1} dry weight) (Ratnakar and Rai 2013).

Casique-Arroyo et al. (2014) assessed the response of salinity stress with respect to variation in betacyanin content in different tissues of *A. hypochondriacus* and its

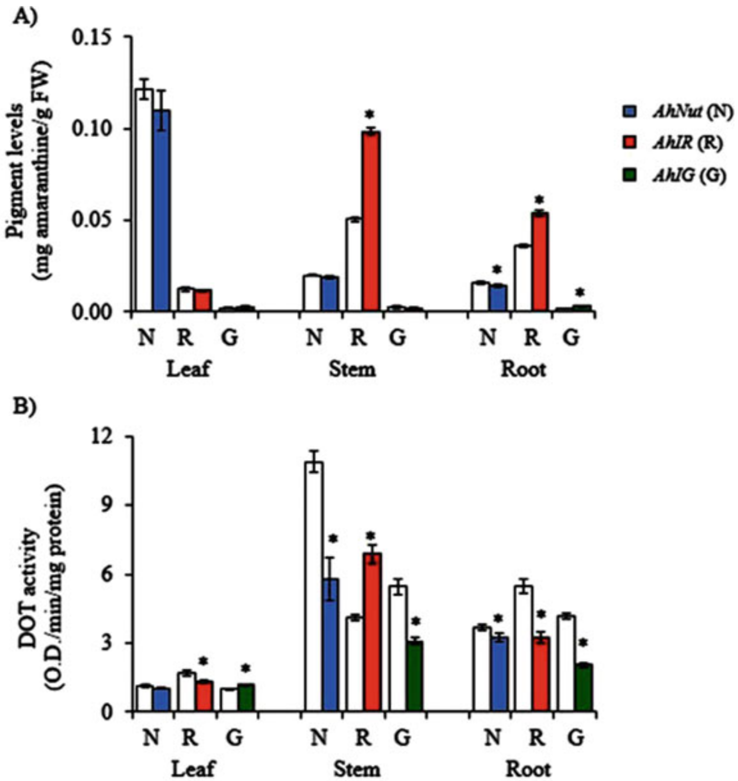

Fig. 10.4 Changes in pigment levels and tyrosinase activity in salt-stressed amaranth plants with contrasting pigmentation patterns (Casique-Arroyo et al. 2014)

association with DOPA oxidation tyrosinase (DOT) activity and betacyanin-biosynthetic gene expression. *AhNut* were plants that had high accumulation of betacyanins, while *AhIR* plants had green leaves with pigmented vascular bundles along with stems having high betacyanins. Both *AhNut* and *AhIR* plants showed varied response to salt-stress. *AhNut* accumulated less betacyanin pigments in all plant tissues, whereas stems and roots of *AhIR* plants showed remarkable increase in the betacyanin content. *AhIG* plants had low levels of betacyanins that was not altered by induction of salinity stress (Fig. 10.4). The DOT activity levels were unaffected or reduced slightly in response to salinity-stress.

10.7 Salt Stress in *Amaranthus*: Molecular Studies

Russell et al. (1998) investigated how the salt and water stresses affect choline monooxygenase (CMO) expression in the C4 plant families Amaranthaceae and Chenopodiaceae (both of order Caryophyllales). *Amaranthus caudatus plants were exposed to* a $NaCl:CaCl_2$ mixture (5.7:1 mol/mol). Treatments were provided after 5 weeks of germination at 1.5 L per pot on a daily basis, and the salt level was elevated by 50 mm every third day till a value of 300 mm was achieved. The CMO cDNA isolated from *Beta vulgaris* hybridized to a salt-inducible 1.9-kb CMO mRNA from *A. caudatus* leaves. The antibodies to spinach CMO recognized an *A. caudatus* CMO polypeptide of 45 kilo Dalton (kD) as the CMO monomer from spinach and beet. The CMO activity in control and salt stressed leaves of *A. caudatus* was found to be at comparable levels to those in leaves of *B. vulgaris* and *Spinacia oleracea*. The CMO mRNA, polypeptide, and enzyme levels in salt stressed leaves significantly increased at 400 mM salt concentration and returned to normalcy on removal of salt stress.

Meng et al. (2001) studied the photosynthetic adaptation mechanism of vegetable amaranth (*A. tricolor*) under salinity stress as a result of the accumulation of glycine betaine (GB), a well- known osmoprotectant. A full length choline monooxygenase (CMO) cDNA (1643 bp) cloned with open reading frame encoded a 442-amino acid long protein, which showed 69% similarity with CMOs in spinach and beet. DNA gel blot analysis showed the presence of a single copy of CMO gene in the genome of *A. tricolor*. The expression of CMO and betaine-aldehyde dehydrogenase (BADH) proteins in amaranth leaves were significantly enhanced under salt stress.

Valdés-Rodríguez et al. (2007) isolated and characterized a complementary DNA (cDNA) from an immature seed cDNA library of *A. hypochondriacus* L. that encoded a cysteine protease inhibitor (*AhCPI*). The encoded polypeptide comprising of 247 amino acids showed significant homology to cystatins of other plant species. Gene expression analyses pointed out that different abiotic stresses significantly enhanced the expression of *AhCPI* in roots and stems. The results showed that in *A. hypochondriacus*, *AhCPI* regulated seed germination and provided protection to the plant against various abiotic stresses.

Cytosolic Ca^{2+} perturbations are known to occur in stresses which play a major role in cross-talk signaling since Ca^{2+} can be elicited in response to various abiotic and biotic stresses (Agarwal and Zhu 2005). Aguilar-Hernandez et al. (2011) used the suppression subtractive hybridization technique to investigate calcium stress responsive-genes in the leaves of *Amaranthus hypochondriacus*. The screening of the libraries led to the generation of 420 upregulated and 199 downregulated transcripts. The metallothionein-2A (AhMT2A), S-adenosyl-l-methionine synthase (AhSAMS), and one homolog of the *Arabidopsis thaliana* universal protein A (AtUspA) was upregulated in response to salt stress albeit to a lesser extent. A novel putative zinc finger protein along with other novel proteins like wall associated kinase (WAK) that connect innermost portion of the cell to the cell wall, phosphoinositide-binding proteins which represent a small fraction of membrane phospholipids, and rhomboid protease (that cut the polypeptide chain of other proteins) were identified in response to calcium stress in the leaves of *A. hypochondriacus*.

Délano-Frier et al. (2011) performed large-scale transcriptome analysis by massive parallel pyrosequencing technology to generate stem- and (a) biotic stress-responsive gene expression profiles for four different stresses, viz., salinity, drought, insect herbivory, and bacterial infection in *Amaranthus hypochondriacus.* Digital expression analysis identified 1971 differentially expressed genes in response to various abiotic stresses. This included many multiple stress-inducible genes that could serve as reservoirs to develop genetically engineered plants showing resistance to abiotic stresses.

The alteration in root protein accumulation in *A. cruentus* plants under salt stress was assessed using 2D gel electrophoresis and liquid chromatography-mass spectrometry/mass spectrometry (LC-MS/MS) technique by Huerta-Ocampo et al. (2014). A total of 101 protein spots were differentially accumulated in response to salinity stress of which 77 were successfully identified using LC-MS/MS and computational biology approaches. The resulting proteins were arranged in different groups on the basis of their biological action. The presence of different protein isoforms varying in their isoelectric point and/or molecular weight pointed toward the presence of revealed the significance of salt stress-induced posttranslational modifications during salt stress conditions. Some stress-responsive proteins like Ah24 that were unique to *A. cruentus* were also identified.

A grain amaranth (*Amaranthus hypochondriacus* cv. Revancha) transcription factor (TF) gene that coded for a class A and cluster I DNA binding with one finger TF (AhDof-AI) were overexpressed in *Arabidopsis thaliana* (Massange-Sánchez et al. 2016) (Fig. 10.5). For salt stress, the plants were first grown in normal soil with normal water for 3 weeks and then irrigated for 3 days with 50 mL solution containing diminishing salt concentrations starting initially with a 400 mM sodium chloride solution. The tolerance to salinity stress increased in all OE-*AhDof-AI* transgenic lines tested (Fig. 10.6). However, no major increase in salt stress tolerance was observed in OE-*AhERF-VII* (Group VII *Arabidopsis* ERF genes) transgenic plants. The transgenic OE-*AhERF-VII* and OE-*AhDof-AI* plants also showed normal vegetative and reproductive development. The glucose level and SOD activity showed significant enhancement in salt stressed conditions in OE-*AhDof-AI* plants. The results showed that the gene provided tolerance to salinity stress without fitness penalties.

Palmeros-Suárez et al. (2017) suggested a role of *AhDGR2* gene, coding for a DUF642 protein in abiotic stress tolerance in grain amaranth (*Amaranthus hypochondriacus*) since it was significantly induced in plants that were provided water and salt stress. The amaranth DGR (DUF642 L-GalL-responsive) gene that was induced under salinity stress modified the cell wall structure and caused hypersensitivity to abscisic acid and salt when overexpressed in *Arabidopsis*.

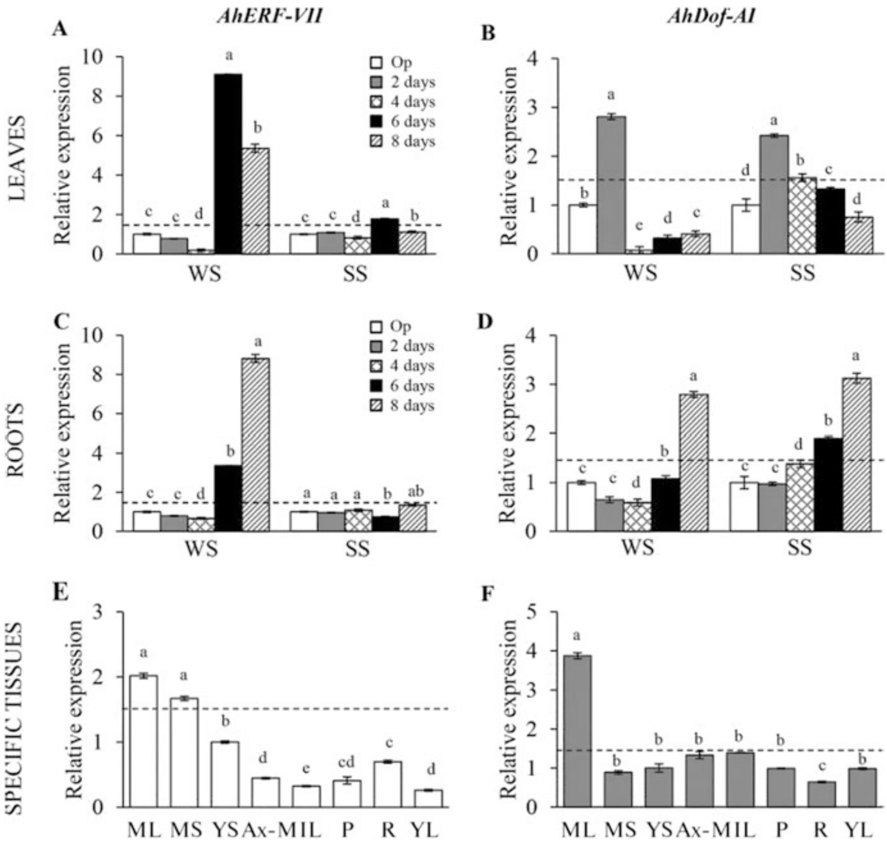

Fig. 10.5 Tissue-specific- and stress-induced expression patterns of the *AhERF-VII* and *AhDOF-AI* transcription factor genes in *A. hypochondriacus* (Massange-Sánchez et al. 2016)

10.8 Conclusion

Amaranth is an underutilized crop for sustainable food production having high nutritional value. The plants show resistance to adverse abiotic stresses, and a deep understanding of amaranth's stress tolerance mechanisms is likely to provide valuable input to improve stress tolerance in the genus.

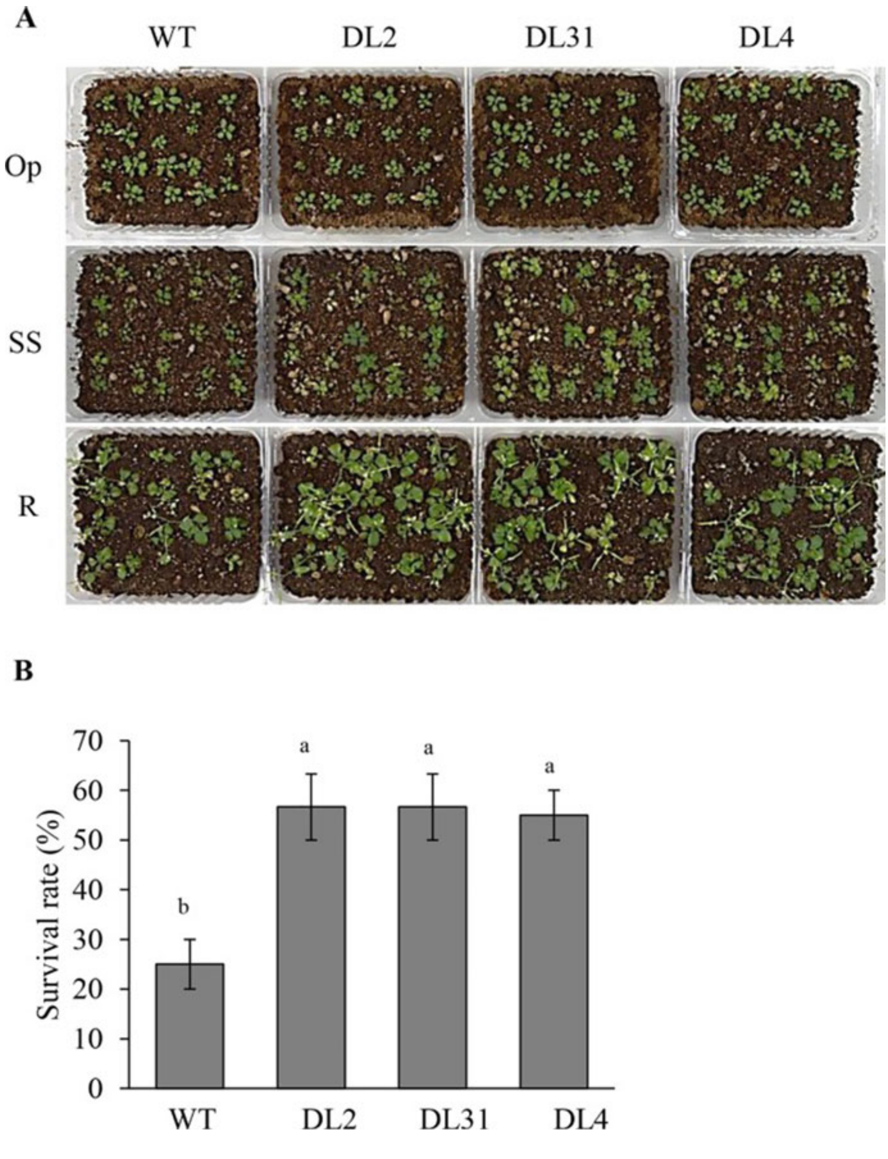

Fig. 10.6 The overexpression of the *AhDOF-AI* gene confers acute salt stress tolerance in transgenic *Arabidopsis* plants (Massange-Sánchez et al. 2016)

References

Agarwal M, Zhu J-K (2005) Integration of abiotic stress signaling pathways. In: Jenks MA, Hasegawa PM (eds) Plant abiotic stress. Blackwell, Oxford, pp 214–247

Aguilar-Hernandez HS, Santos L, Leon-Galvan F, Barrera-Pacheco A, Espitia-Rangel E, De León-Rodríguez A, Guevara-González RG, Barba de la Rosa AP (2011) Identification of calcium stress induced genes in amaranth leaves through suppression subtractive hybridization. J Plant Physiol 168:2102–2109

Allen P (1961) Die Amaranthaceen Mittleleuropas Carl Verlag, Munchen

Bhargava A, Srivastava S (2013) Quinoa: botany, production and uses. CABI

Bhargava A, Shukla S, Chatterjee A, Singh SP (2003) Relative selection efficiency for foliage yield and quality characters in vegetable *Chenopodium* over different cuttings. J Appl Hortic 5:85–86

Bhargava A, Shukla S, Chatterjee A, Singh SP (2004) Selection response in vegetable amaranth (*A. tricolor*) for different foliage cuttings. J Appl Hortic 6:43–44

Bhatnagar-Mathur P, Vadez V, Sharma KK (2008) Transgenic approaches for abiotic stress tolerance in plants: retrospect and prospects. Plant Cell Rep 27:411–424

Bialecka B, Kepczynski J (2009) Effect of ethephon and gibberellin A3 on *Amaranthus caudatus* seed germination and α- and β-amylase activity under salinity stress. Acta Biol Cracov Ser Bot 51(2):119–125

Boscaiu M, Lull C, Lidon A, Bautista I, Donat P, Mayoral O, Vicente O (2008) Plant responses to abiotic stress in their natural habitats. Bull UASVM Hortic 65:53–58

Casique-Arroyo G, Martínez-Gallardo N, González de la Vara L, Délano-Frier JP (2014) Betacyanin biosynthetic genes and enzymes are differentially induced by (a)biotic stress in *Amaranthus hypochondriacus*. PLoS One 9(6):e99012

Castrillón-Arbeláez PA, Frier JPD (2016) Secondary metabolism in *Amaranthus* spp. – a genomic approach to understand its diversity and responsiveness to stress in marginally studied cops with high agronomic potential. In: Shanker A (ed) Abiotic and biotic stress in plants – recent advances and future perspectives. InTech, pp 185–227. https://doi.org/10.5772/61820

Chinnusamy V, Zhu JK (2003) Plant salt tolerance. Top Curr Genet 4:241–270

Cramer GR, Urano K, Delrot S, Pezzotti M, Shinozaki K (2011) Effects of abiotic stress on plants: a systems biology perspective. BMC Plant Biol 11:163

da Costa DMA, de Souza Melo HN, Ferreira SR, Dantas JA (2008) Conteúdo de N, P, K^+, Ca^{2+} e Mg^{2+} no amaranto (*Amaranthus* spp.) sob estresse salino e cobertura morta. Rev Ciênc Agron 39:209–216

Délano-Frier JP, Avilés-Arnaut H, Casarrubias-Castillo K, Casique-Arroyo G, Castrillón-Arbeláez PA, Herrera-Estrella L, Massange-Sánchez J, Martínez-Gallardo NA, Parra-Cota FI, Vargas-Ortiz E, Estrada-Hernández MG (2011) Transcriptomic analysis of grain amaranth (*Amaranthus hypochondriacus*) using 454 pyrosequencing: comparison with *A. tuberculatus*, expression profiling in stems and in response to biotic and abiotic stress. BMC Genomics 12:363

FAO (Food and Agricultural Organization) (2010) FAO land and plant nutrition management service. www.fao.org

Francios LE, Mass EV (1994) Crop response and management on salt affected soils. In: Pessaraki M (ed) Handbook of plant and crop stress. Marcel Dekker, New York, pp 149–180

Gaikwad DK, Chavan PD (1995) Effect of salt stress on some antinutritional factors in *Amaranthus* species. Acta Bot Hung 38:355–362

Gaikwad DK, Chavan PD (1998) Salinity induced changes in stomatal behaviour and water relations in three *Amaranthus* species. Ann Plant Physiol 12:119–125

Gaikwad DK, Chavan PD (1999) Effect of salinity on carbohydrate status of three *Amaranthus* species. Acta Bot Hung 42:111–117

Greenway H, Munns R (1980) Mechanisms of salt tolerance in nonhalophytes. Annu Rev Plant Physiol 31:149–190

Grime JP (1979) Plant strategies and vegetation process. Wiley, New York

Hao J-H, Lv S-S, Bhattacharya S, Fu J-G (2017) Germination response of four alien congeneric *Amaranthus* species to environmental factors. PLoS One 12:e0170297

Huerta-Ocampo JA, Briones-Cerecero EP, Mendoza-Hernandez G, De Leon-Rodriguez A, de la Rosa APB (2009) Proteomic analysis of amaranth (*Amaranthus hypochondriacus* L.) leaves under drought stress. Int J Plant Sci 170:990–998

Huerta-Ocampo JA, Leon-Galvan MF, Ortega-Cruz LB, Barrera-Pacheco A, De Leon-Rodriguez A, Mendoza-Hernandez G, de la Rosa AP (2011) Water stress induces up-regulation of DOF1 and MIF1 transcription factors and down-regulation of proteins involved in secondary metabolism in amaranth roots (*Amaranthus hypochondriacus* L.). Plant Biol 13:472–482

Huerta-Ocampo JA, Barrera-Pacheco A, Mendoza-Hernández CS, Espitia-Rangel E, Mock HP, Barba de la Rosa AP (2014) Salt stress-induced alterations in the root proteome of *Amaranthus cruentus* L. J Proteome Res 13:3607–3627

Jamil M, Lee DB, Jung KY, Ashraf M, Lee SC, Rha ES (2006) Effect of salt (NaCl) stress on germination and early seedling growth of four vegetable species. J Cent Eur Agric 7:273–282

Johnson BL, Henderson TL (2002) Water use patterns of grain amaranth in the northern Great Plains. Agron J 94:1437–1443

Katiyar RS, Shukla S, Rai S (2000) Varietal performance of grain amaranth *(A. hypochondriacus*) on sodic soil. Proc Nat Acad Sci (India) 70:185–187

Kauffman CS, Weber LE (1990) Grain amaranth. In: Janick J, Simon JE (eds) Advances in new crops. Timber Press, Portland, OR, pp 127–139

Luo W, Sun Y (2012) Effects of NaCl stress on the germination characteristics of amaranth seeds. In: Jin D, Lin S (eds) Advances in future computer and control systems. Advances in intelligent and soft computing, vol 160. Springer, Berlin

Madhusoodanan KJ, Pal M (1981) Cytology of vegetable Amaranths. Bot J Linn Soc 82:61–68

Massange-Sánchez JA, Palmeros-Suárez PA, Espitia-Rangel E, Rodríguez-Arévalo I, Sánchez-Segura L, Martínez-Gallardo NA, Alatorre-Cobos F, Tiessen A, Délano-Frier JP (2016) Overexpression of grain amaranth (*Amaranthus hypochondriacus*) AhERF or AhDOF transcription factors in *Arabidopsis thaliana* increases water deficit- and salt-stress tolerance, respectively, via contrasting stress-amelioration mechanisms. PLoS One 11:e0164280

Meena KK, Sorty AM, Bitla UM, Choudhary K, Gupta P, Pareek A, Singh DP, Prabha R, Sahu PK, Gupta VK, Singh HB, Krishanani KK, Minhas PS (2017) Abiotic stress responses and microbe-mediated mitigation in plants: the omics strategies. Front Plant Sci 8:172

Menezes RV, Azevedo Neto AD, Oliveira Ribeiro M, Cova AMW (2017) Growth and contents of organic and inorganic solutes in amaranth under salt stress. Pesq Agropec Trop 47:22–30

Meng YL, Wang YM, Zhang DB, Nii N (2001) Isolation of a choline monooxygenase cDNA clone from *Amaranthus tricolor* and its expressions under stress conditions. Cell Res 11:187–193

Mengel K, Kirkby EA (1982) Principles of plant nutrition. International Potash Institute, Bern

Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59:651–681

Murata S, Kobayashi M, Matoh T, Sekiya J (1992) Sodium stimulates regeneration of phosphoenolpyruvate in mesophyll chloroplasts of *A. tricolor*. Plant Cell Physiol 33:1247–1250

NRC (National Research Council) (1984) Amaranth: modern prospects for an ancient crop. National Academy Press, Washington, DC

Odjegba VJ, Chukwunwike IC (2012) Physiological responses of *Amaranthus hybridus* L. under salinity stress. Indian J Innov Dev 1:742–748

Omamt EN, Hammes PS, Robbertse PJ (2006) Differences in salinity tolerance for growth and water-use efficiency in some amaranth (*Amaranthus* spp.) genotypes. N Z J Crop Hortic Sci 34:11–22

Pal M (1972) Evolution and improvement of cultivated amaranths. I. Breeding system and inflorescence structure. Proc Indian Nat Sci Acad 38:28–37

Pal M, Khoshoo TN (1965) Grain amaranths. National Botanical Gardens, Lucknow

Pal M, Khoshoo TN (1972) Evolution and improvement of cultivated amaranths (v. Inviability, weakness and sterility in hybrids). J Hered 63:78–82

Pal M, Khoshoo TN (1974) Grain amaranth: evolutionary studies in world crops: diversity and change in Indian subcontinent. Cambridge University Press, London

Palmeros-Suárez PA, Massange-Sánchez JA, Sánchez-Segura L, Martínez-Gallardo NA, Rangel EE, Gómez-Leyva JF, Délano-Frier JP (2017) *AhDGR2*, an amaranth abiotic stress-induced DUF642 protein gene, modifies cell wall structure and composition and causes salt and ABA hyper-sensibility in transgenic *Arabidopsis*. Planta 245:623–640

Rastogi A, Shukla S (2013) Amaranth: a new millennium crop of nutraceutical values. Crit Rev Food Sci Nutr 53:109–125

Ratnakar A, Rai A (2013) Effect of NaCl salinity on β-carotene, thiamine, riboflavin and ascorbic acid contents in the leaves of *Amaranthus polygamous* L. var. Pusa Kirti. Octa J Environ Res 1:211–216

Ribeiro JEMM, Combrink NJJ (2006) *Amaranthus tricolor* L. leaf yields affected by salinity, harvesting stage and harvesting methods. South Afr J Plant Soil 23:29–37

Robert-Seilaniantz A, Bari R, Jones JDG (2010) Abiotic or biotic stresses. In: Pareek A, Sopory SK, Bohnert HJ, Govindjee (eds) Abiotic stress adaptation in plants: physiological, molecular and genomic foundation, Springer, New York, pp 103–122

Russell BL, Rathinasabapathi B, Hanson AD (1998) Osmotic stress induces expression of choline monooxygenase in sugar beet and amaranth. Plant Physiol 116:859–865

Sauer J (1967) The grain amaranths and their relatives: a revised taxonomic and geographic survey. Ann Missouri Bot Gard 54:103–137

Shannon MC, Grieve CM, Francois LE (1994) Whole-plant response to salinity. In: Wilkinson RE (ed) Plant environment interactions. Marcel Dekker, New York, pp 199–244

Shukla S, Singh SP (2000) Studies on genetic parameters in vegetable amaranth. J Genet Breed 54:133–135

Shukla S, Bhargava A, Chatterjee A, Srivastava A, Singh SP (2006) Genotypic variability in vegetable amaranth (*Amaranthus tricolor* L.) for foliage yield and its contributing traits over successive cuttings and years. Euphytica 151:103–110

Shukla S, Bhargava A, Chatterjee A, Pandey AC, Mishra BK (2010) Diversity in phenotypic and nutritional traits in vegetable amaranth (*Amaranthus* tricolor): a nutritionally underutilized crop. J Sci Food Agric 90:139–144

Simontacchi M, Galatro A, Ramos-Artuso F, Santa-Maria GE (2015) Plant survival in a changing environment: the role of nitric oxide in plant responses to abiotic stress. Front Plant Sci 6:977

Stavridou E, Hastings A, Webster RJ, Robson PRH (2017) The impact of soil salinity on the yield, composition and physiology of the bioenergy grass *Miscanthus* × *giganteus*. GCB Bioenergy 9:92–104

Suma S, Ambika SR, Kazinczi G, Narwal SS (2002) Allelopathic plants. 6. Amaranth spp. Allelopathy J 10:1–11

Tucker JB (1986) Amaranth: the once and future crop. Bioscience 36:9–13

USSL (United States Salinity Laboratory) (2005) George E. Brown Jr. Salinity laboratory. USDA-ARS, Riverside, CA

Valdés-Rodríguez S, Guerrero-Rangel A, Melgoza-Villagómez C, Chagolla-López A, Delgado-Vargas F, Martínez-Gallardo N, Sánchez-Hernández C, Délano-Frier J (2007) Cloning of a cDNA encoding a cystatin from grain amaranth (*Amaranthus hypochondriacus*) showing a tissue-specific expression that is modified by germination and abiotic stress. Plant Physiol Biochem 45:790–798

Wang Y, Nii N (2000) Changes in chlorophyll, ribulose bisphosphate carboxylase-oxygenase, glycine betaine content, photosynthesis and transpiration in *Amaranthus tricolor* leaves during salt stress. J Hortic Sci Biotechnol 75:623–627

Wang Y, Meng Y-L, Ishikavva H, Hibino T, Tanaka Y, Nii N, Takabe T (1999) Photosynthetic adaptation to salt stress in three-color leaves of a C4 plant *Amaranthus tricolor*. Plant Cell Physiol 40:668–674

Wouyou A, Gandonou CB, Montcho D, Kpinkoun J, Kinsou E, Komlan FA, Gnancadja SL (2016) Salinity resistance of six amaranth (*Amaranthus* sp.) cultivars cultivated in Benin at germination stage. Int J Plant Soil Sci 11:1–10

Zhu JK (2001) Plant salt tolerance. Trends Plant Sci 6:66–71

Chapter 11
Tef (*Eragrostis tef*): A Superfood Grain from Ethiopia with Great Potential as an Alternative Crop for Marginal Environments

Aweke M. Gelaw and Asad S. Qureshi

Abstract Most marginal lands are found in arid and semi-arid regions of the world, which account for about 19% of global land area and are home to 25% of the global population. About 41% of the population in these areas depends on agriculture as the major source of its livelihood. However, production of major staple food crops in these areas is affected by many biophysical constraints, among which drought and salinity are the major ones. In contrast, some neglected and underutilized crop species are known to be more resilient and better adapted to grow under those abiotic stresses. Tef is one of such crops that can adapt to such environments and play an important role in eradicating hunger, malnutrition, and poverty. It is a traditional crop that grows very well under various stress conditions in Ethiopia, but little known elsewhere. For example, its water requirement is approximately 15–30% lower than that of barley. And there is no significant difference in yield and water productivity of tef between a full irrigation and a 25% deficit irrigation distributed throughout its growth stages. Further, some laboratory experiments showed presence of broad intraspecific variation among tef accessions and varieties. Tef grain contains higher amount of several minerals than wheat, barley, or grain sorghum, and its straw as feed is also preferred by livestock to any other cereal straws.

Keywords Abiotic stress · Drought · Salt tolerance · Ethiopia

11.1 Introduction

Biophysically, marginal lands have low inherent productivity for agriculture; are fragile and exposed to degradation for slope and/or climate; and have high agricultural risk due to climate and disease. Further, marginal lands support a high

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proportion of the rural poor livelihoods. Land fragility and high density of poor population is leading to accelerated erosion and vegetation destruction with a significant negative externality (FAO 1999).

Most marginal lands are in dry areas (arid and semi-arid regions) of the world, which are about three billion hectares (19% of global land area) and are home to more than 1.7 billion people (25% of the global population). 41% of the population in these areas depends on agriculture as the major source of its livelihood (Kidane 2014). Among the biophysical constraints in these environments are low soil fertility, poor drainage, shallow depth, salinity, steepness of terrain, and unfavorable climatic conditions such as drought (FAO 1999).

The major staple food crops as rice, maize, and wheat are sensitive to marginal environments. Neglected and underutilized crop species, NUCS are key resources to challenge and improve agricultural production in marginal lands (Rao et al. 2014). NUCS are known to be more resilient and better adapted than common staple crops to grow in marginal environments with water scarcity, poor soil fertility and other such yield-limiting factors. Tef (*Eragrostis tef (Zucc.) Trotter*) is one of the crops which can become as a strategy for fighting hunger, malnutrition, and poverty in marginal environments. It is a traditional crop that grows under different stresses in Ethiopia, but little known elsewhere. Tef can be adapted to a broader range of agro-climatic environments from sea level to 2800 meter above sea level (m.a.s.l) under different relative humidity, soil conditions, air temperature, and rainfall (Ketema 1997). It can tolerate anoxic situations better than maize, wheat, and sorghum (Kinfemichael and Fisseha 2011), easy to store, and can resist to weevils and other pests (Tadesse 1969). Tef grain contains higher amount of several minerals than wheat, barley, or grain sorghum (Hager et al. 2012; Baye 2014); Tef straw is also suitable like other cereal straws and can fetch premium price (Ketema 1997). Nevertheless, its geographically restricted use as in Ethiopia only, tef has been one of the least scientifically studied crops.

The aim of this paper is to review some of the significant advantages of tef as an alternative food crop and food nutritional security and as income source generation for smallholder farmers in harsh environments beyond Ethiopia.

11.2 History of Tef Production in Ethiopia

Tef is a C_4-metabolism warm season annual grass plant of medium stature, and a short growth duration period, self-pollinated (Ayele et al. 1996; Ketema 1997; Fig. 11.1). It has narrow-folded leaf blades and a fibrous root with erect stems, and some genotypes are bending or elbowing types. The panicle type of inflorescence is from loose to compact. Is an allotetraploid plant $2n = 4\times = 40$ (estimated genome size of 730 Mbp) (Degu and Fujimura 2010)? Tef belongs to the grass family *Poaceae*. The genus *Eragrostis* includes 350 species (Watson and Dallwitz 1992).

Fig. 11.1 Different varieties of tef plants

Eragrostis tef is an endemic specie to Ethiopia, and exact date and location of domestication is unknown. The Ethiopian farmer has grown tef as far back as recorded history goes. Fewer reports are published on the agriculture history of tef (Mengesha 1966). Ethiopia is the center of origin for tef (Vavilov 1951). Little quantities of tef seeds were found in two ancient relics: (1) in 1866 in a brick of the old Egyptian pyramid of Dassur, built in 3359 B.C., and (2) in 1867 in a brick taken from the ruins of the ancient Jewish town of Ramses in Egypt (1300 B.C.) (Ketema 1997). It was then concluded that tef was grown in Egypt before the thirteenth century B.C. However, the seeds found in those sites were those of *Eragrostis pilosa* (L.) P.B., which apparently grows abundantly in Egypt (Mengesha 1966). It is, therefore, most probable that the matured plants of *E. pilosa* were then used to solidify the clay bricks. Even now, the same method of plastering and solidifying mud walls with tef. straw is commonly practiced in rural Ethiopia.

Ethiopia and partly Eritrea are the only countries in the world that use tef as a cereal food crop. The species is cultivated for its hay in a few other places of the world, such as Kenya, South Africa, and Australia and recently in the USA and Netherlands. In Ethiopia, the production of tef exceeds all other cereal crops. In 2013/2014 cropping season, it occupied 31% of the cultivated area and 20% of production of the total cereal crops in the country (CSA 2014). Moreover, tef is adapted to the changing agro-climatic conditions in Ethiopia with reduced production risks (Jabesa and Abraham 2016). Tef cultivars are recognized and described based on the grain color. Tef grain ranges in color from milky white to almost dark brown (Fig. 11.2). The common colors are white, creamy white, light brown, and dark brown.

Most Ethiopian farmers use local landraces of tef and are distributed all over the country. Local genotypes such as *Gea-Lame*, *Dabi*, *Shewa-Gimira*, *Beten* and *Bunign* are early physiological maturity (<85 days) and are cultivated in areas with low period humidity (Ketema 1997). The same genotypes are also cultivated in areas with enough rainfall and where double-cropping is practiced. Other local tef. landraces such as *Alba, Ada*, and *Enatit* are cultivated in highly productive regions of

Fig. 11.2 Different colors (dark brown to white) of tef grains

Table 11.1 Modern tef varieties for dry land areas of Ethiopia

Variety	Yield potential		Best adaptation areas	
	Grain (tha^{-1})	Straw (tha^{-1})	Altitude (m.a.s.l.)	Rainfall (mm)
DZ-Cr-385 (Sidama)	1.2–1.8	6.5–8.0	1350–1700	300–600
DZ-Cr387 Ril 127 (*Gemechis*)	1.5–2.2	–	1450–1700	600–1950
DZ-Cr-37 (*Tsedey*)	1.4–2.2	8.2–9.0	1600–2000	300–700
DZ-01-96 (*Magna*)	1.4–2.8	8.2–9.0	1800–2400	300–700
HO-Cr-136 (*Amarech*)	1.3–1.8	–	1600–1700	300–800
DZ-01-1681 (*key tena*)	1.6–2.5	8.4–9.3	1600–2000	300–500
DZ-01-354 (*Enatit*)	1.7–2.8	8.5–13.0	1600–2400	300–700
DZ-01-99	1.7–2.2	8.5–13.0	1400–2400	300–700
DZ-Cr-44	1.7–2.8	12.5–14.0	1800–2400	300–700

Source: Kidane and Dejene (2010)

the country where environmental stress is not severe. In the past few decades, few modern varieties were released by the national agricultural research system (NARS) to adapt for different agroecological systems of the country. The most widely used modern varieties particularly for dry areas are indicated below (Table 11.1).

11.3 Role of Tef for Food Security in Ethiopia

Tef is a major staple food crop in Ethiopia. Its grain is mainly used for making *injera*, the main national dish in Ethiopia. Tef is also valued for its fine straw used for animal feed and the straw mixed with mud for construction. In 2012/2013 cropping season, tef covered about 2.7 million hectares and was cultivated by 6.3 million farmers with total national production of 3.5 million ton valued at 1.6 billion USD (CSA 2013). Moreover, both the demand and price of the grain has risen recently to the point it has become a luxury food for the rural poor (GRO 2014). For example, urban consumption per capita of tef in Ethiopia at 61 kg per year is significantly higher than its rural per capita consumption at 20 kg year^{-1} (GRO 2014). The lower consumption of tef grain by the poor is for its high price, which typically was twice as high compared to cheapest cereal of maize (GRO 2014).

The rise in demand and price of tef. is encouraging farmers to produce it as a cash crop. Nowadays most farmers in major tef.-producing areas of Ethiopia produce for market by its high price and lack of alternative cash crops (Demeke and Di Marcantonio 2013). At national level, it is the second most important cash crop after coffee, with a commercial surplus value of 464 M USD or one quarter lower than coffee (599 M USD) in 2011/2012 season but equivalent to the commercial surplus of the three other main cereals combined (sorghum, maize, and wheat) during the same season (Minten et al. 2013).

In Ethiopia, tef. is mainly cultivated as a cereal crop food product. Further, farmers valorize its straw and use as a source of animal feed, particularly, in dry season. Indeed, most parts of Ethiopia feed tef. straw for cattle, calves, and working oxen. However, its price is always much higher than other straw grasses. Tef as a livestock forage lies in its palatability, highly nutritive, low albumin ratio, high yield, rapid growth, drought resistance, and its ability to smother weeds (Ketema 1997; Fufa et al. 2011). In a nutshell, tef is an important crop in Ethiopia as farm income and food security.

11.4 Nutritional Facts and Health Benefits

In Ethiopia, there are three main categories of tef according to grain color, white, red, and mixed; and there are considerable differences in mineral contents among the three categories. However, all categories are superior in mineral contents than other common cereals (Baye 2014) (Table 11.2). Further, the dietary fiber content of tef is several folds higher than that of wheat, sorghum, rice, and maize (Bultosa 2007; Hager et al. 2012). The reason for the higher dietary fiber content of tef may be that whole grains have higher fiber content than decorticated ones; tef is always eaten in the whole-grain form: the germ and bran are consumed along with the endosperm.

Tef grain contains ~13% protein higher than in sorghum, maize, wheat, and rice (Hager et al. 2012). It has an adequate balance of essential amino acids and high values of methionine and cystine (Mulugeta 1978 in Ketema 1997). The mineral content in tef is also good. Its iron and calcium contents are especially notable. Tef grain contains high amount of calcium, copper, zinc, manganese, and phosphorous than wheat, maize, rice, and sorghum (Hager et al. 2012; Fig. 11.3).

The amino acid composition of grain tef is comparable to egg protein, but not in lower lysine content. However, it is possible to improve the tef diet by supplementing with fenugreek (*Trigonella foenum-graecum*) (Chichaibelu 1965). Moreover, the traditional way of consuming tef *injera* with *wot*, a sauce made of

Table 11.2 Mineral content of tef grain compared to major cereals (mg g^{-1})

Mineral	White	Red	Mixed	Maize	Sorghum	Wheat	Rice
Iron	9.5–37.7	11.6 – >150	11.5– >150	3.6–4.8	3.5–4.1	3.7	1.5
Zinc	2.4–6.8	2.3–6.7	3.8–3.9	2.6–4.6	1.4–1.7	1.7	2.2
Calcium	17–124	18–178	78.8–147	16	5.0–5.8	15.2–39.5	23
Copper	2.5–5.3	1.1–3.6	1.6	1.3	0.41	0.23	0.16

Source: Abebe and Ronda (2014), Baye et al. (2014), Gebremariam et al. (2012), Kebede (2009), USDA/ARS (2014)

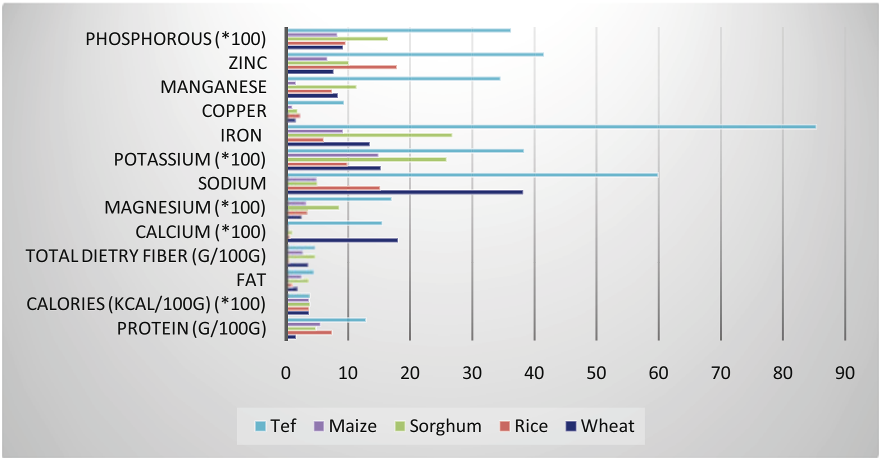

Fig. 11.3 Nutritional tef grain content compared to maize, sorghum, rice, and wheat (adapted from Hager et al. 2012)

meat or lentil, faba-bean, field pea, broad bean and chickpea, can give a near optimal amino acid mixture (lysine and sulfur-containing amino acids) (Ketema 1997).

Tef. diet also has health benefits, in contrast wheat, rye, and barley are harmful, and rice and corn are harmless to people that must follow a gluten-free diet. Most gluten-free cereal foods (e.g., bread, pasta, cold cereal) made from refined flour do not contain iron and B vitamins. Thus, a gluten-free diet containing adequate amounts of fiber, iron, thiamin, riboflavin, niacin, and folate is needed. Tef has high iron content, has good amino acid composition, and lacks gluten-protein (Thompson 2000). This makes tef an ideal addition in the list of products developed to patients with celiac disease by even increasing the nutritional value of their gluten-free diet. However, the potential of tef. grain is not limited to gluten-free diets. Its starch has low glycemic acid content, and its high-quality protein composition, which is comparable with egg protein, is an ideal protein source for children between 2 and 5 years old (Thompson 2000). Further, in Ethiopia, an absence of anemia related to pregnancy seems to correlate with the areas of tef consumption because of the grain benefit by good iron content and high blood hemoglobin in tef consumers (Molineaux and Biru 1965; Tadesse 1969; Ketema 1997).

11.5 Ecological Adaptation

World population is increasing and is expected to reach from seven to nine billion by 2050 year (UN DESA 2015). The worldwide agricultural productivity is subject to increasing environmental constraints. Several abiotic constraints are causing significant reduction in food productivity particularly in dry land areas of the world. Drought and salinity are the most important abiotic limitations by their high magnitude of impact and wide distribution in these regions (Bartels and Sunkar 2007). In consequence, to reduce these losses are a major concern for many countries to cope with the increasing food requirements of their growing population. Finding crop species which can tolerate these stresses and produce food and feed in such environments is critical.

Tef is cultivated as a cereal crop in Ethiopia from long-time, and it is well known for its versatility and withstanding crop to extreme environmental constraints. It grows in wide ranges of altitudes and under different soil conditions and diverse moisture and temperature regimes in Ethiopia (Fig. 11.4). Generally, tef is an annual warm seasonal grass and genetically adapted for cultivating in warmer climates. As a C_4 grass plant probably in the early Oligocene (c.a. 30 million years ago) (Sage 2004). C_4 plants have more photosynthetic capacity and efficient use of nitrogen and water (Sheehy et al. 2007).

Moreover, in comparison with other cereal crop plants, tef grain is less prone to attacks by weevils and other storage pests; it may be attributed to its small size and hard seed cover (Tadesse 1969). Tef grain is perhaps the smallest among carbohydrate-rich kernels, with an individual grain size of 0.9–1.7 mm (length) and 0.7–1.0 mm (diameter), oval-shaped grain weight of 0.2–0.4 mg (Bultosa 2007; Belay et al. 2009; Gebremariam et al. 2014). The seeds can remain viable for several years, in a safely stored traditional conditions with no chemical protection.

11.5.1 Adaptation to Drought

Drought is a major challenge for food production in dry lands, synonymously called “water stress lands”, and it affects 45% of the world land area (Shahid and Al-Shankiti 2013). Extreme rainfall variability and unpredictable droughts are typical features of dry land ecosystems. These features present significant constraints for intensive agriculture in these areas. Regardless of these constraints, agriculture is the mainstay of dry land rural economies, and therefore, optimization of the scarce water and soil resources is often a matter of survival for millions of rural poor living in these areas (FAO 1999).

In Ethiopia, drought is widespread in the dry land (arid and semi-arid) areas of the country, which covers over 60% of its total land area (Kidane 2014). Current production of tef in Ethiopia is increasing more than ever in those areas replacing

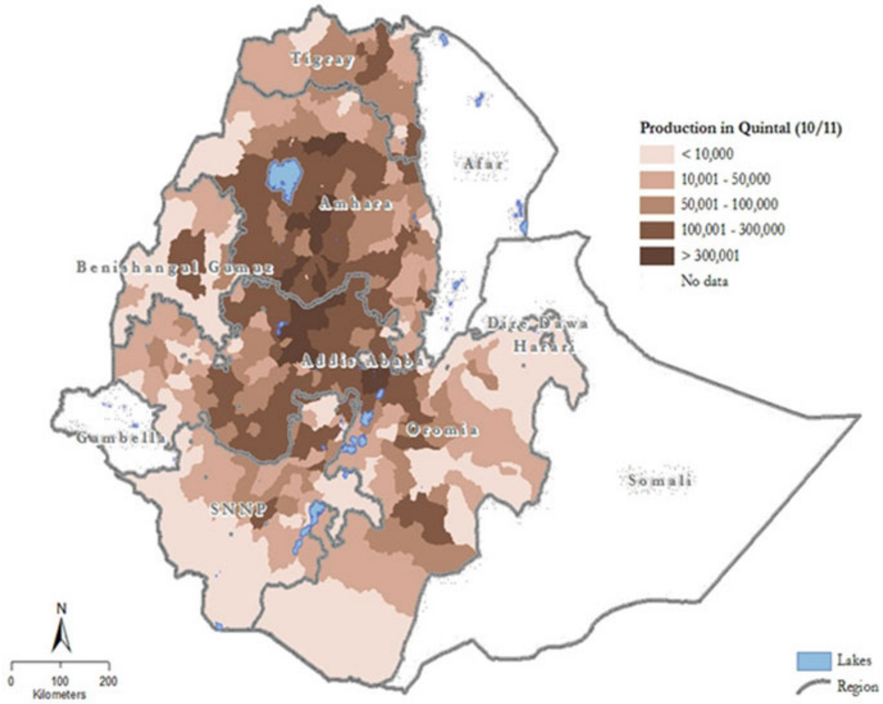

Fig. 11.4 Estimated tef grain production in quintals (100 kg) across Ethiopian regions in 2010/11 cropping season (adapted from Kedir et al. 2014)

sorghum and maize because of its relative drought tolerance and the fact that it matures early when sorghum and maize usually fail. Usually, tef is cultivated in Ethiopia as a staple or pillar crop. As a staple, it is planted in moisture-enough areas as other cereals, commonly sown late and harvested in dry season. During dry seasons or late onset of rains, the production area of tef can increase. As a standby crop, in moisture-deficit areas, farmers wait until the main crops (maize and sorghum) show signs of failing. Then, they sow early growth tef variety to save crop food production in case of disaster (Kidane and Dejene 2010). That is why, in many areas in Ethiopia where recurrent moisture stress occurs, tef production replaces that of maize, sorghum, and other staples (Ketema 1997). That is why many farmers and growers say tef is a reliable cereal under unreliable climates (Ketema 2002).

Although tef is usually planted when the soil is wet, the stages of growth at which tef encounters frequent drought include the seedling, vegetative, and reproductive stages. Farmers find that moderate drought stress at both the seedling and vegetative stages is advantageous, as the yield of tef is not reduced and may even be increased because of compensatory growth and the development of an increased number of tillers when rainfall recommences (Takele 2001). However, drought occurring during the anthesis and grain filling stages is critical since this drought substantially

Table 11.3 Grain and biomass yield response of tef to different irrigation deficit treatments in Rift Valley region of Ethiopia (adapted from Yihun et al. 2013)

Irrigation treatment	Amount of irrigation water applied (mm)	Grain yield (t ha^{-1})	Biomass yield (t ha^{-1})	Relative yield reduction
0% deficit (full irrigation)	380	3.30	14.0	0.00
25% deficit	294	3.18	11.2*	0.04
50% deficit	225	2.52*	6.7**	0.24
75% deficit	156	0.66**	4.5**	0.80

* $p < 0.05$; ** $p < 0.01$. Used K_c values for tef crop were for the initial, mid, and late season stages 0.8–1.0, 0.95–1.1, and 0.4–0.5 (Araya et al. 2011)

reduces yield. This is because drought reduces the translocation of non-structural carbohydrates from the source to the sink and consequently reduces grain yield (Takele 2001).

There was a general subjective assumption by many agronomists in Ethiopia on tef water requirement is high like for wheat and barley. However, tef crop needs 15–30% irrigation, which is less than used for barley (Araya et al. 2011). No significant difference in yield and water productivity of tef between a full irrigation and a 25% deficit irrigation distributed throughout its growth stages was found (Yihun et al. 2013; Table 11.3). Thus, 25% water-deficit irrigation is recommended in areas where water is scarce, and it is an appropriate way to use water in regions with scarce hydric resources.

Drought tolerance is one of the many traits needed in a crop cultivar; progress in breeding on it seems to be a practical and economical solution. However, the genetic improvement of drought tolerance in crop plants requires the identification of relevant morphological and physiological traits as selection criteria (Blum et al. 1982). The National Tef Breeding Program in Ethiopia has attempted to develop drought-resistant tef cultivar. However, it has been slow mainly because knowledge based on the morphological and physiological traits for drought resistance in tef. is lacking (Takele 2001).

However, the limited research efforts carried out in the past indicated that there is tremendous morphological and physiological variability in tef genotypes (Takele 1997; Shiferaw and Baker 1996; Ayele 1993). The mode of adaptation to drought stress in tef is avoidance mechanism, i.e., the crop may avoid drought stress by conserving water either by reducing the area of transpiration through a reduction in leaf size or by stomatal closure (Shiferaw and Baker (1996). Further, drought tolerance in tef is variable within cultivars (Degu et al. 2008). Root growth and osmotic adjustment are major mechanisms—it is possible that substantial root growth might increase the ability of a seedling to absorb water during drought and osmotic adjustment to sustain photosynthesis and water uptake (Degu et al. 2008).

Some experimental results also showed significant variations for osmotic adjustment (OA) among tef genotypes (Ayele et al. 2001) suggesting that the trait could be manipulated by genetic improvement for drought resistance. The range of OA value is relatively high and comparable to sorghum, millet, and turf grass (Qian and Fry 1997). However, extended survival of high OA in tef lines is not reflected in higher shoot dry weight increase, i.e., root depth has no significant association with OA across tef germplasm (Ayele et al. 2001). Possibly, the slower growth during stress of the higher OA lines contributed to solute accumulation and a higher OA. Therefore, OA appears to improve plant survival under stress in tef lines (Ayele et al. 2001). This survival strategy is typical of natural vegetation and in tef seems to be more like natural vegetation type than to a modern improved domesticated crop. Furthermore, *DZ-01- 99*, a variety with specific adaptation to optimum moisture environment in Ethiopia, has higher OA than *DZ-01-354*, a tef variety widely adapted in drought prone areas (Ayele et al. 2001).

Moreover, there was a general expectation that drought-resistant tef germplasm in terms of OA capacity would be more prevalent in low altitude (and drier) regions. However, there is no association between tef OA capacity and altitude of the region of origin for the germplasm materials (Ayele et al. 2001). This leads to a conclusion that it may be possible that temperature and/or soil type are also important in affecting tef adaptation to different altitudes, besides the moisture factor. Hence, future exploration of high OA materials should consider germplasm collection from different altitudes under different temperatures and/or soil types.

11.5.2 Adaptation to Salinity

Salinity is a growing problem worldwide, and in Ethiopia, 11.033 million hectares of land is salt affected, which is first in Africa. Saline soils are prevalent in the Rift Valley and other lowland areas. It is expected that salinity will affect more land in the years to come as the country is introducing and implementing small- and large-scale irrigation schemes in these areas to increase its food production. Finding genetically salt-tolerant genotypes in important crops such as tef is very critical to achieve the objective of food self-sufficiency under the inevitable problem of salt build up in these irrigation farms.

Salt tolerance is not a constant trait over the plant's life cycle is the plant capacity to grow in a substrate that contains soluble salt (Ungar 1974; Parida and Das 2005). Few studies conducted in Ethiopia hitherto regarding selection and testing tef genotypes for salt tolerance showed presence of broad variation among tef accessions and varieties. The variations are more pronounced amid accessions, and it would allow more salinity tolerant lines to be selected from existing tef. germplasm (Kinfemichael and Fisseha 2009). Germination in improved tef varieties *DZ-01-354* and *DZ-Cr-37* is not significantly influenced by salinity up to 4 dS m^{-1} at room temperature (Mamo et al. 1996), and the variety *DZ-Cr-37* and other two accessions (# 212928 and #237186) are able to attain more than 75% final germination percentage (FGP) under a water salinity of 12 dS m^{-1} (Kinfemichael and Fisseha 2009). Besides, the accession #237186 and the variety *DZ-Cr-37* have better yield than other varieties and accessions at higher water salinity levels (Kinfemichael and Fisseha 2011).

Overall, there are variations in salinity tolerance among tef varieties and accession at different stages of its. Since large tef. crop germplasm bank already exist in Ethiopia, further screening of these collections could be carried out to identify useful genetic sources of tolerance.

11.6 Conclusion

Tef is a major food crop in Ethiopia where it is annually cultivated on more than 3 M ha of land. However, it is still in the list of orphan crops since it is cultivated only in Ethiopia as a staple crop and has not been focused in global crop improvement programs. Compared to other cereal crops, tef is resistant to drought and salinity. Besides, unlike other cereals, the seeds of tef can be easily stored under local conditions without losing viability and are resistant to weevil attack. Besides, *Eragrostis tef* grain is a rich source as nutraceutical food product and gluten-free seed. Recent studies found that iron bio-availability is significantly higher in tef bread than in wheat bread. This indicates that consuming tef can prevent anemia, one of the major public health problems in developing countries accounting for three quarters of one million deaths a year in Africa and Southeast Asia. To sum up, tef provides quality a grain food and grows in marginal conditions and poorly suited to other cereal crops. Tef, as a NUCS, is a key alternative crop to challenge and improve agricultural production in marginal lands where major staple food crops are sensitive.

References

Abebe W, Ronda F (2014) Rheological and textural properties of tef (*Eragrostis tef* (Zucc.) Trotter) grain flour gels. J Cereal Sci 60(1):122–130. https://doi.org/10.1016/j.jcs.2014.02.001

Araya A, Stroosnijder L, Girmay G, Keesstra S (2011) Crop coefficient, yield response to water stress and water productivity of teff (*Eragrostis tef* (Zucc.)). Agric Water Manag 98:775–783. https://doi.org/10.1016/j.agwat.2010.12.001

Ayele M (1993) Use of excised-leaf water content in breeding tef (*Eragrostis tef* (Zucc.) Trotter) for moisture stress areas. Acta Agron Hung 42:261–265

Ayele M, Dolezel J, Van DM, Brunner H, Zapata-Arias FJ (1996) Flow cytometric analysis of the nuclear genome of the Ethiopian cereal tef [*Eragrostis tef* (Zucc.) Trotter]. Genetica 98:211–215. https://doi.org/10.1007/BF00121369

Ayele M, Blum A, Nguyen HT (2001) Diversity for osmotic adjustment and root depth in tef [*Eragrostis tef* (Zucc) Trotter]. Euphytica 121:237–249

Bartels D, Sunkar R (2007) Drought and salt tolerance in plants. Crit Rev Plant Sci 24:23–58. https://doi.org/10.1080/07352680590910410

Baye K (2014) Teff: nutrient composition and health benefits. Ethiopia Strategy Support Program (ESSP), Ethiopian development Research Institute (EDRI) and International Food Policy Research Institute (IFPRI) joint Working paper 67

Baye K, Mouquet-Rivier C, Icard-Verniere C, Picq C, Guyot J-P (2014) Changes in mineral absorption inhibitors consequent to fermentation of Ethiopian *injera*: implications for predicted iron bioavailability and bioaccessibility. Int J Food Sci Technol 49(1):174–180. https://doi.org/10.1111/ijfs.12295

Belay G, Zemede A, Assefa K, Metaferia G, Tefera H (2009) Seed size effect on grain weight and agronomic performance of tef (*Eragrostis tef* (Zucc.) Trotter). Afr J Agric Res 4:836–839

Blum A, Mayer J, Gozlan G (1982) Infrared thermal sensing of plant canopies as a screening technique for dehydration avoidance in wheat. Field Crops Res 5:137–147

Bultosa G (2007) Physicochemical characteristics of grain and flour in 13 Tef [*Eragrostis tef* (Zucc.) Trotter] grain varieties. J Appl Sci Res 3:2042–2051

Chichaibelu B (1965) Studies on the biological evaluation of the protein quality of teff (*Eragrostis abyssiniva*) and abish (*Trigonclla foenvm-graecum*) and the supplementary value of clash when added to tef. Unpublished Master's thesis, Cornell University, Ithaca, New York

CSA (2013) Central Statistics Agency (CSA) Agricultural Sample Survey 2012/2013, vol 1. Report on area and production for major crops (private peasant holding meher season) statistical Bulletin, Addis Ababa, Ethiopia

CSA (2014) Central Statistics Agency (CSA) Agricultural Sample Survey 2013/2014 Vol. 1. Report on area and production for major crops (private peasant holding meher season) statistical Bulletin, Addis Ababa, Ethiopia

Degu HD, Fujimura T (2010) Mapping QTLs related to plant height and root development of *Eragrostis tef* under drought. J Agric Sci 2:1916–9760

Degu HD, Ohta M, Fujimura T (2008) Drought tolerance of *Eragrostis tef* and development of roots. Int J Plant Sci 169:768–775. https://doi.org/10.1086/588064

Demeke M, Di Marcantonio F (2013) Analysis of incentives and disincentives for tef in Ethiopia, MAFAP, SPAAA

FAO (1999) Food and Agriculture Organization of the United Nations (FAO) report of the Technical Advisory Committee (TAC) study on CGIAR Research Priorities for Marginal Lands. http://www.fao.org/Wairdocs/TAC/X5784E/x5784e05.htm#chapter2. Accessed 02 Jan 2017

Fufa B, Behute B, Simons R, Berhe T (2011) Strengthening the tef value chain in Ethiopia. Mimeo, Agricultural Transformation Agency (ATA), Addis Ababa

Gebremariam MM, Zarnkow M, Becker T (2012) Tef (*Eragrostis tef*) as a raw material for malting, brewing and manufacturing of gluten-free foods and beverages: a review. J Food Sci Technol 51:1–15. https://doi.org/10.1007/s13197-012-0745-5

Gebremariam MM, Zarnkow M, Becker T (2014) Teff (*Eragrostis tef*) as a raw material for malting, brewing and manufacturing of gluten-free foods and beverages: a review. J Food Sci Technol 51:2881–2895. https://doi.org/10.1007/s13197-012-0745-5

GRO Intelligence (2014) Tef: an emerging Ethiopian "super food"

Hager AS, Wolter A, Jacob F, Zannini E, Arendt EK (2012) Nutritional properties and ultra-structure of commercial gluten free flours from different botanical sources compared to wheat flours. J Cereal Sci 56:239–247. https://doi.org/10.1016/j.jcs.2012.06.005

Jabesa K, Abraham T (2016) Performance of yield attributes, yield and economics of tef (*Eragrostis tef*) influenced by various row spacing, nitrogen and phosphorus fertilizers. Afr J Plant Sci 10:234–237. https://doi.org/10.5897/AJPS2016.1430

Kebede Z (2009) Levels of essential elements in three tef [*Eragrostis tef* (Zucc.) Trotter] varieties. Addis Ababa University

Kedir M, Schmidt E, Tilahun H (2014) Teff production and market access in Ethiopia. A paper presented at the Ethiopian Economics Association (EEA) and the Econometric Society 19th annual conference of the African Region Chapter of the Econometric Society and 12th international conference on the Ethiopian Economy, July 16–19, 2014, Addis Ababa, Ethiopia

Ketema S (1997) Tef (*Eragrostis tef* (Zucc.)) Trotter. Promoting the conservation and use of underutilized and neglected crops. 12. Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute, Rome

Ketema S (2002) Evaluation of tef (*Eragrostis tef*) cultivars for nitrogen use efficiency in Ethiopia

Kidane G (2014) Agricultural and pastoral technologies and practices for climate change adaptation in lowland dryland areas of Ethiopia, A paper presented at the High-Level Policy Forum, 6–7 March 2014, Semera, Afar National Regional State of Ethiopia

Kidane G, Dejene A (2010) Agricultural based livelihood systems in dry lands in the context of climate change: inventory of adaptation practices and technologies of Ethiopia. FAO Publication no. 38, Rome

Kinfemichael G, Fisseha I (2009) Screening some tef [*Eragrostis tef* (Zucc.) Trotter] accessions/varieties for salt tolerance during germination and seedling stage. CNCS, Department of Biology, Mekele University, vol 1(2), pp 17–29

Kinfemichael G, Fisseha I (2011) Effects of salinity on yield and yield components of teff [*Eragrostis tef* (Zucc.) Trotter] accessions and varieties. Curr Res J Biol Sci 3:289–299

Mamo T, Richter C, Heiligtag B (1996) Response of some varieties of durum wheat and tef to salt stress. Afr Crop Sci J 4:423–432

Mengesha MH (1966) Chemical composition of Tef (*Eragrostis tef*) compared with that of wheat, barley and grain sorghum. Econ Bot 20:268–273. https://doi.org/10.1007/BF02904277

Minten B, Tamru S, Engida E, Kuma T (2013) Ethiopia's value chains on the move: the case of Teff. Ethiopia strategy support program II. Working paper 52, Addis Ababa, Ethiopia

Molineaux L, Biru M (1965) Tef consumption, hookworm infestation and hemoglobin levels: a preliminary report. J Health 51:1–5

Parida AK, Das AB (2005) Salt tolerance and salinity effects on plants: a review. Ecotoxicol Environ Saf 60(1):324–349. https://doi.org/10.1016/j.ecoenv.2004.06.010

Qian Y, Fry JD (1997) Water relations and drought tolerance of four turfgrasses. J Am Soc Hortic Sci 122:129–133

Rao NK, Shahid M, Al Shankiti A, Elouafi I (2014) Neglected and underutilized species for food and income security in marginal environments. In: Aldous et al. DE (eds) Proceedings. Middle East Horticultural Summit. Acta Hort. 1051, ISHS 2014

Sage RF (2004) The evolution of C_4 photosynthesis. New Phytol 161:341–370. https://doi.org/10.1111/j.1469-8137.2004.00974.x

Shahid AS, Al-Shankiti A (2013) Sustainable food production in marginal lands—case of GDLA member countries. Int Soil Water Conserv Res 1:24–38

Sheehy JE, Mitchell PL, Hardy B (2007) Charting new pathways to C_4 rice. International Rice Research Institute, Los Baños, 422 p

Shiferaw B, Baker DA (1996) An evaluation of drought screening techniques for *Eragrostis tef*. Trop Sci 36:74–85

Tadesse E (1969) Tef (*Eragrostis tef*): the cultivation, usage and some of the known diseases and insect pests, part I. Debre Zeit Agricultural Experiment Station Bulletin No. 60. Alemaya University of Agriculture, Dire Dawa, Ethiopia

Takele A (1997) Genotypic variability in dry matter production, partitioning and grain yield of tef (*Eragrostis tef* [Zucc.] Trotter) under moisture deficit. Sinet: Ethiop J Sci 20:177–188

Takele A (2001) Canopy temperatures and excised leaf water loss of Tef (*Eragrostis tef* (Zucc.) trotter) cultivars under water deficit conditions at Anthesis. Acta Agron Hungar 49:109–117. https://doi.org/10.1556/AAgr.49.2001.2.1

Thompson T (2000) Folate, iron, and dietary fiber contents of the gluten free diet. J Am Dietetic Assoc 100:1389–1396

UN DESA (2015) World population prospects: the 2015 revision, key findings and advance tables. United Nations, Department of Economic and Social Affairs, Population Division (UN DESA) working paper no. ESA/P/WP.241

Ungar I (1974) The effect of salinity and temperatures on seed germination and growth of *Hordeum jabatum*. Can J Bot 52:1357–1362

USDA/ARS (U.S. Department of Agriculture, Agricultural Research Service) (2014) USDA National Nutrient Database for Standard Reference, Release 27. Nutrient Data Laboratory Home Page: http://www.ars.usda.gov/ba/bhnrc/ndl. Accessed December 2018

Vavilov NI (1951) The origin, variation, immunity and breeding of cultivated plants. Translated from the Russian by K. Starr Chester. The Ronald Press Co., New York, pp 37–38

Watson L, Dallwitz M (1992) The grass genera of the world. CAB International, Wallingford, Oxford, 1038 p

Yihun YM, Haile AM, Schultz B, Erkossa T (2013) Crop water productivity of irrigated tef in a water stressed region. Water Resour Manag 27:3115–3125. https://doi.org/10.1007/s11269-013-0336-x

Chapter 12
Safflower: A Multipurpose Crop for the Marginal Lands

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Abstract Both soil and water salinity reduce the crop productivity in agricultural lands throughout the world. To cope with this scourge, we need crops that can be cultivated successfully in the marginal lands with salt problem. To explore salinity tolerance in safflower, a field experiment comprising of six cultivars was conducted using low (0.3 dS/m) and high (15 dS/m) saline water. Eight morphological and agronomic traits including days to flowering, petal life, plant height, number of branches/plant, number of capitula/plant, number of seeds/capitulum, seed yield/plot, and 100-seed weight were studied to compare the performance of the safflower genotypes at two different salinities. High salinity accelerated the flowering time by about 3 days and decreased the petal life by 2 days. Due to high saline water treatment, plant height of the safflower genotypes reduced on average by 21%, number of capitula 28%, number of seeds per capitulum 16%, 100-seed weight 12%, and seed yield about 25%. On the other hand, salinity had negligible effect on the number of branches. The results indicate that safflower has the potential to be cultivated in the region with salinity problem as an oil seed, fodder, and floriculture crop.

Keywords Safflower · Salinity · Marginal lands · Agronomic traits · Oilseed crop

12.1 Introduction

Safflower (*Carthamus tinctorius* L.) is a multiuse crop grown in various regions of the world, which provides many benefits to the farmers. An enormous diversity exists among the safflower genotypes cultivated in different parts of the world

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Photo 12.1 A safflower field experiment at ICBA

(Jaradat and Shahid 2006). *Carthamus tinctorius* L. is a part of the huge daisy family (Asteraceae/Compositae) with its center of origin in the near east where the species was cultivated for the first time about 4000 years ago (Harlan 1992; Zohary and Hopf 2000) (Photo 12.1). It is an annual shrub with many branches (Photo 12.2) that have rotund flower head called capitulum at their tops, which is surrounded by stiff bracts (Photo 12.3). After germination, seedling produces cluster of leaves called rosette. After about 4 weeks, main middle stem appears that may grow to 25–150 cm in length at the flowering time. Leaves on branches and stems have many stiff spikes that discourage grazing mammals like camels, goats, and sheep to feed on them. Its flowers, which are composite, have 20–180 florets and have white, yellow, orange, or red colors. Safflower seed, which is white in color with four sides, has smooth and dense hull (Photo 12.4). The seed length is 6–7 mm and about 40 mg in weight that makes around 25,000 seeds per kg. The plant has deep taproot that may grow up to 4 m in the soil (Oyen and Umali 2007). Due to its taproot, safflower absorbs NO_3 leachates left in the groundwater and is therefore regarded to be good for environment (Yau and Ryan 2010).

Safflower seed contains 24–36% oil (Lee et al. 2004), which is without color and flavor, and its nutritive value is more like sunflower oil. Based on different fatty acid compositions, safflower has two kinds of oil, i.e., monounsaturated and polyunsaturated produced by diverse genotypes. Its monounsaturated form is more or less like olive oil as it has about 15% linoleic acid and 80% oleic acid, which is best for frying. Different researches show that regular usage of the oil can reduce body fat and enlarge muscle. It assists in fighting coronary diseases and diabetes (Ramsden et al. 2013; Norris et al. 2009). Standard type of polyunsaturated oil comprises

Photo 12.2 The safflower plants in field

Photo 12.3 Capitulum of safflower

around 15% oleic acid and 80% linoleic acid, which is apt for salad oil and smooth margarine manufacturing (Oelke et al. 1992). Because this kind of oil polymerizes at high temperature, it is good for cooking particularly frying. This class of oil is also being utilized in the manufacturing of biodiesel, make-ups, drugs, lubricants, paints, and lacquer. After squeezing of oil from safflower seed, the residual meal that has

Photo 12.4 The safflower seeds

about 40% protein is a good feed for chickens and cattle. Apart from oil production, it is used as feedstuff for wild and pet birds.

Safflower petals are used to make various products. They are dried to make a low-cost substitute for saffron with nearly similar savor and color (Photo 12.5). Because artificial pigments and dyes are harmful to health, a few of them can be replaced with bright safflower petals. Besides coloring, the safflower petals also have some medicinal values to treat arthritis, hypertension, infertility, rheumatism, and some other diseases. Its flowers are being used in Ayurvedic and traditional Chinese medicines for centuries (Chevallier 1996).

Safflower plant has a great potential to be cultivated as a forage crop (Heuzé and Tran 2017). The spineless varieties can be cultivated as a fodder for livestock at any stage, whereas thorny safflower cultivars are used at initial phase when there are no spines. Green plants of safflower make high-quality silage to feed livestock during winter (Landau et al. 2004). Usage of safflower as feedstuff helps to enhance considerably the rate of fertility in female sheep (Stanford et al. 2001). On average, safflower produces around 22 tons per hectare of dry biomass with fine edibility.

The colorful flowering plant has a great potential to be used as an ornamental (Bradley et al. 1999). Different varieties of safflower can be used in home gardens as well as for landscaping. They are usually grown in greenhouses for cut flowers, and their demand is increasing in the flower markets (Uter 2008).

The safflower plants grow nicely in comparatively well-drained and deep soils. Sandy loam soil, which has better water-holding ability is, most suitable for it. At the time of germination, the required optimal temperature is about 15 °C, whereas at flowering 25–32 °C allows the better seed production. Its seed rate varies from 10 to

Photo 12.5 Dried safflower petals at a local market in Dubai

25 kg/ha depending on the seed size with 50cm row to row distance. In dry area its seed production is around 500 kg/ha; on the other hand, in the irrigated farmland its grain yield can be 1000 kg/ha, but the yield can be increased two folds with better farm management techniques. For the safflower seed production, Mexico is on the top followed by Kazakhstan, India, USA, Russia, Turkey, and China in world production of safflower (World Production of Safflower Seeds 2015).

Safflower can be grown in the marginal lands with water and salinity problems. It is a drought-tolerant plant (Safavi et al. 2013), which grows fine in semi-dry and arid regions with availability of water at time of planting. The safflower root system is wide, deep, and robust, that can break tough subsoil forming channels in soil to make water and air movement possible there (Oyen and Umali 2007). Because of its strong and extensive roots, the plant can endure lengthy dry spells by drawing deep lying water to the extent of 4 m.

Since safflower is a relatively salt-tolerant multipurpose crop, its cultivation on saline soils can be beneficial. Moderately saline water (8 dS m^{-1}) could be utilized to water safflower crop without any significant seed yield loss (Bassil and Kuffka 2002). Hence, the crop is usually grown in many of the salt-affected areas (Kaya et al. 2003). Salinity at medium level (6.8 dS m^{-1}) does not alter either its seed harvest or oil quality; however it affects the germination of its seed (Francois et al. 1964). The crop might assist in hindering the advance of brininess in dry regions. Due to its deep root system (Knowles 1989) and lengthy growing period, the crop supports in decreasing the underground saline water from recharge zones to impede the spread of salinity in addition to waterlogging in the affected regions.

In farmlands where birds and pest animals are problems to various crops, safflower can be grown there successfully with little maintenance as its spines deter those pests. Safflower helps in controlling different cereal diseases by disrupting the life cycles of the responsible microbes when it is cultivated in between two dissimilar crops. Growing of safflower in agriculture farms used for cereals cultivation is easier as it doesn't require more work for field preparation.

For better safflower cultivation in salinity-affected areas, it is very important to have useful information on the impacts of salinity on different characteristics including yield components of the crop. For these reasons, field experiments comprising of six safflower cultivars at two different salinity levels were carried out to find out the effect of salt on the crop.

12.2 Materials and Methods

The yield trials were carried out during cropping season of 2008 at the field experimental facilities of International Center for Biosaline Agriculture (ICBA), Dubai, United Arab Emirates (25°05′ N and 055°23′ E). The area where the experiment was conducted has mild winter and hot summer (Table 12.1). The texture of the ICBA soil is sandy, which is fine sand (sand 98%, silt 1%, and clay 1%), somewhat alkaline (pH 8.22) calcareous (about 60% $CaCO_3$ equivalents), and porous (45% porosity). The soil has very high drainage capacity with 26% saturation, whereas the electrical conductivity of its saturated extract (ECe) is 1.2 dS m^{-1}. Based on the classification of American Soil Taxonomy (Soil Survey Staff 2010), the soil of ICBA is Typic Torripsamments, carbonatic, and hyperthermic (Shahid et al. 2009).

Six safflower accessions, ICBA S-13, ICBA S-14, ICBA S-15, ICBA S-115, ICBA S-142, and ICBA S-438, were tested in the experiment. Two treatments, low salinity (0.3 dS/m), which was the control, and ground water with high salinity

Table 12.1 Dubai weather during 2011

	Temperature			Precipitation	Average relative humidity (%)			Sunshine hours
Month	Max	Avg.	Min		Max	Avg.	Min	
January	24 °C	21 °C	19 °C	0.00 mm	89%	65%	36%	255
February	29 °C	22 °C	18 °C	0.00 mm	98%	65%	34%	232
March	29 °C	24 °C	19 °C	0.00 mm	86%	63%	27%	256
April	33 °C	29 °C	23 °C	0.00 mm	80%	55%	20%	298
May	37 °C	33 °C	28 °C	0.00 mm	76%	53%	17%	347
June	39 °C	35 °C	33 °C	0.00 mm	82%	51%	19%	342
July	41 °C	37 °C	33 °C	0.00 mm	82%	54%	25%	322
August	41 °C	37 °C	34 °C	0.00 mm	83%	56%	29%	316
September	38 °C	35 °C	32 °C	0.00 mm	86%	56%	24%	309
October	34 °C	31 °C	28 °C	0.00 mm	86%	55%	23%	303
November	30 °C	26 °C	22 °C	0.00 mm	87%	59%	29%	285
December	24 °C	21 °C	19 °C	0.00 mm	89%	64%	37%	260

(15 dS/m), were used to evaluate the salinity tolerance of the 6 safflower genotypes. As the soils have a low nutrient content, a compost (animal) was applied at the rate of 40 tonnes per hectare (t ha^{-1}) in the experimental field before sowing. After 30 days of sowing, urea (45%) @ 30 kg ha^{-1}, while 8 weeks later NPK (20:20:20) @ 40 kg ha^{-1} was applied to the experiment.

12.2.1 Experimental Design

The seed of every experimental cultivar was planted in a plot of 7.5 m^2; one each for low and high salinity treatments. Plots were randomized in an augmented design. The row to row distance was 50 cm, while the spacing between plants was 25 cm. To lessen/eliminate the border effect, which exists at the edge of field, four rows of a local barley cultivar were planted around the experimental area. The sowing was done by hand in the second week of January.

12.2.2 Irrigation and Water Use

For water supply to the experimental plots, drip irrigation system was used with spacing of 25 cm between the emitters. Water was given @ 1.2 L/day/emitter to the both treatments. For 2 weeks, low saline water was used to both sets of the plots, and afterward saline water treatment was started. The chemical analysis of the saline water used in the experiment is provided in Table 12.2.

12.2.3 Data Recording

In the third week of May, most of the characteristics, including plant height, number of branches per plant, number of capitula per plant, number of seeds per capitulum, seed yield per plot, and 100-seed weight were studied for the both treatments at the time of maturity. For the study of these traits, data on five plants from each plot were recorded. The other traits that were also measured were days to flowering and petal life. The data were analyzed using standard statistical methods to determine the significant differences among the safflower lines for the eight different morphological and agronomic characteristics at two different salinity levels.

Table 12.2 ICBA groundwater chemical analysis

Units			meq L^{-1}	SAR (mmol $L^{-1})^{0.5}$
pH	–	7.35	–	–
Electrical conductivity (EC)	dS/m	15.2	–	–
Sodium (Na^{+})	Mg L^{-1}	4810	209	24
Magnesium (Mg^{2+})	Mg L^{-1}	555	46	
Calcium (Ca^{2})	Mg L^{-1}	423	21	
Potassium (K^{+})	Mg L^{-1}	104	3	
Boron (B^{+})	Mg L^{-1}	1.80	1	
Strontium (Sr^{+})	Mg L^{-1}	9.0	0.1	
Chloride (cl^{-})	Mg L^{-1}	5122	145	
Sulfate ($SO_4{}^{2-}$)	Mg L^{-1}	1620	34	
Total hardiness as $CaCO_3$	Mg L^{-1}	3180	32	
Bicarbonate ($HCO_3{}^{-}$)	Mg L^{-1}	60	1	
Carbonate ($CO_3{}^{-}$)	Mg L^{-1}	Nil	–	
Fluoride (F^{-})	Mg L^{-1}	1.75	0.1	
Sulfide (S^{2-})	Mg L^{-1}	0.01	–	

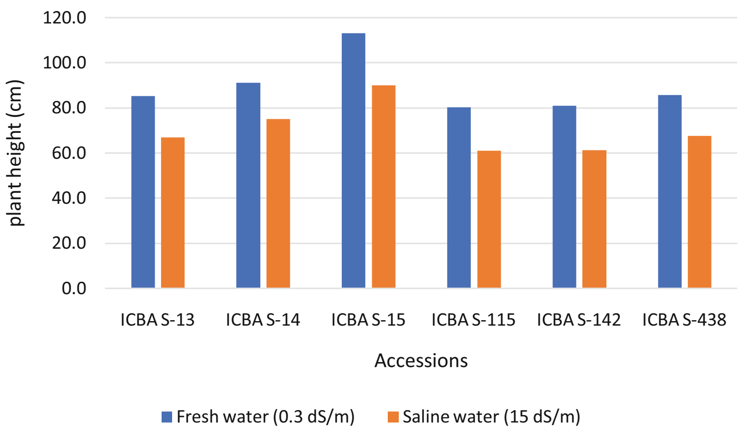

Fig. 12.1 Plant heights of 6 safflower lines at high and low salinity levels

12.3 Results and Discussion

12.3.1 Plant Height

Height is one of the traits of a crop that indicates its suitability as a fodder. Taller plants are considered to be better fodder as they usually have more mass then the shorter ones. The results show that ICBA S-15 was the tallest (113.2 cm) among the six safflowers genotypes tested in the experiment followed by ICBA S-14 (91.2), while ICBA S-115 with 80.4 cm of height was the shortest (Fig. 12.1).

For the trait, salinity affects ICBA S-142 the maximum as it decreases its height to more than 24%, whereas the least effected line is ICBA S-14 that show less than 18% reduction in its stature (Fig. 12.1). ICBA S-15 which is the only accession that has more than 1 m height can be used as a fodder crop. The salinity reduces its stature by about 20%, which is the second best in the experimental lines, making it suitable as forage plant for the marginal lands with salt problems. On average, the reduction in height due to high salinity was recoded around 21% for the 6 safflower accessions. The change in plant stature because of salinity was also observed by Francois et al. (1964) Irving et al. (1988), Bassil and Kuffka (2002) and Feizi et al. (2010) in safflower.

12.3.2 Number of Branches per Plant

The greater number of branches also suggests the superior mass for the plant which makes it desirable trait for fodder purpose. For this plant characteristic, ICBA S-14 showed the highest number (12) followed by ICBA S-13 that has ten branches per plant (Fig. 12.2). On the other hand, the least number of branches were recorded in ICBA S-438 (6). The data as well indicate the presence of big variation among the accessions for the trait as the different between the two extreme lines is around 50%.

Salinity doesn't have much negative effect on the number of branches (Fig. 12.2). In fact, in three of the accessions (ICBA S-15, ICBA S-115, and ICBA S-142), the number of branches has slightly increased due to saline water treatment. For other cultivars, there is a decline in the branch number because of increase in salinity, though it is trivial. The results suggest that the salinity (15 dS/m) may not have conspicuous negative effect on the number of branches per plant in safflower.

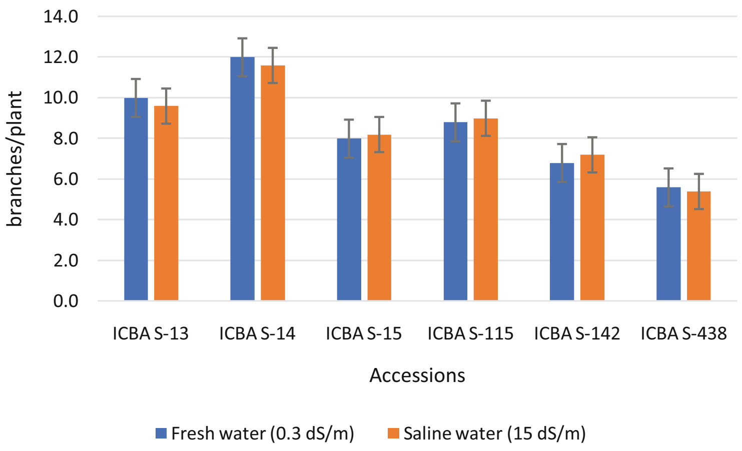

Fig. 12.2 Effect of salinity on number of branches per plant in six safflower genotypes

12.3.3 Number of Capitula per Plant

This trait of safflower plant determines the seed yield of the crop. Higher number of capitula per plant indicates the potential of greater seed production for a genotype. During the study, it was found that ICBA S-15 had the maximum number of capitula per plant (33), while with only nine, ICBA S-348 produced the lowest number (Fig. 12.3). This characteristic exhibits immense variation among the six experimental safflower lines.

Salinity has a biggest negative impact on ICBA S-15 for the trait as it reduces its capitula number to 33%. The high saline water treatment has effected other genotypes in the range of 21–31%. On average, the decrease in capitula per plant for the six safflower genotypes was around 28%. High salinity reducing the number of flowering heads was also shown by Francois et al. (1964), Janardhan et al. (1986), Irving et al. (1988), Feizi et al. (2010) and Siddiqi et al. (2011) in safflower.

12.3.4 Number of Seeds per Capitulum

The amount of seeds possesses by safflower capitulum is associated with its yield per plant. Greater number of seed per capitulum indicates the prospect of higher yield for the safflower genotype. The maximum number of seed per plant, i.e., 37 was recorded for the genotype ICBA S-438 followed by ICBA S-142 that had 32, while the lowest quantity of seed (14) was noted in ICBA S-115.

On average, saline water treatment decreases the seeds in the capitulum of the 6 safflower cultivars by about 16%. The accession ICBA S-13 showed the least effect of salinity on its number of seeds (4%), whereas with 21% decline in seed number ICBA S-114 was the most affected line for this capitulum trait (Fig. 12.4).

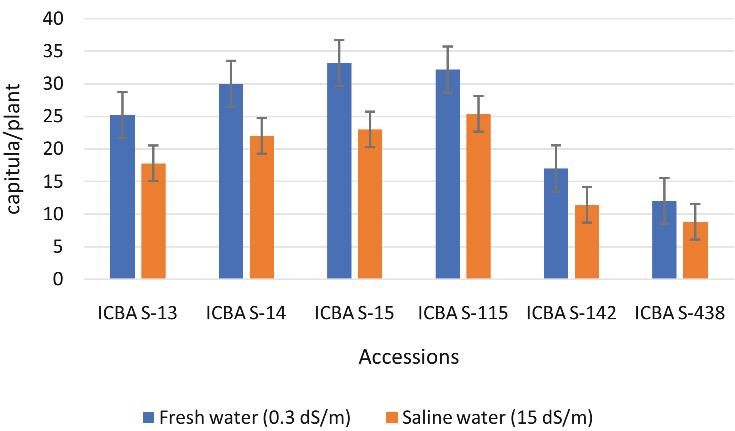

Fig. 12.3 Number of capitula per plant for six safflower genotypes at two salinity levels

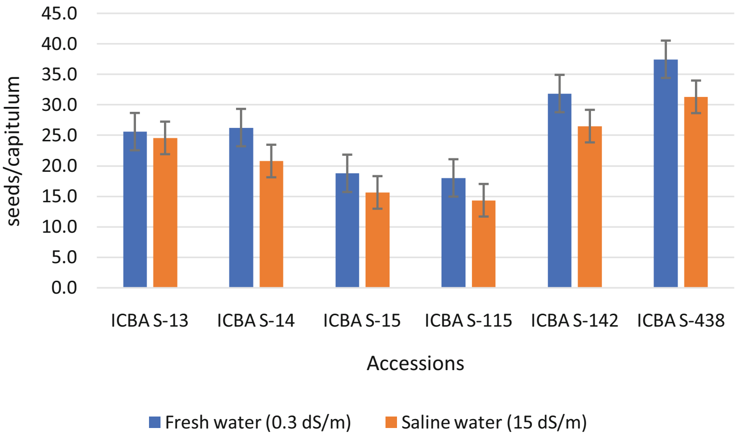

Fig. 12.4 Impact of salinity on number of seeds per capitulum in safflower

Janardhan et al. (1986) and Irving et al. (1988) also found similar decrease in number of seeds per capitulum at higher salinity level.

12.3.5 Seed Yield per Plot

It is considered to be the most important characteristic of the crop that specifies the importance of a safflower cultivar for a particular region. During the study, it was found that ICBA S-438 gave the maximum yield of 1368 g/7.5 m^2. On the other hand, the lowest yield was recorded for ICBA S-115, which produced 813 g per plot that is almost 40% less than the first one.

Salinity has a negative impact on the seed yield of all the safflower genotypes studied in the experiment (Fig. 12.5). The least affected line was ICBA S-13 where the decrease was less than 20%, while for ICBA S-15 the yield reduction was recorded more than 34%. Averagely the decline in the seed yield was around 23%. In a field trial comprising of 8 safflower genotypes, Janardhan et al. (1986) found 9 to 68% decrease in seed yield due to saline water (12 dS/m) treatment. Other researches (Francois et al. 1964; Janardhan et al. 1986; Irving et al. 1988; Feizi et al. 2010; Siddiqi et al. 2011) also observed the reduction in safflower seed yield owing to high saline water.

12.3.6 100-Seed Weight

The “100-seed weight” is one of the yield components of safflower and is usually positively correlated with its seed yield. The characteristic is also a measure of seed

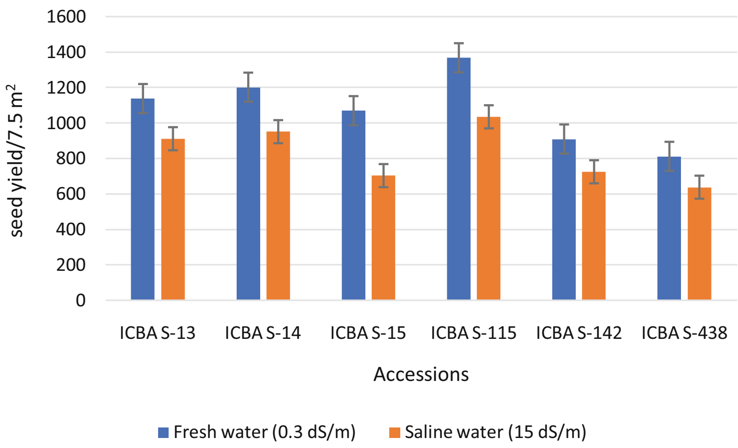

Fig. 12.5 Performance of six safflower genotypes for seed yield at two salinity levels

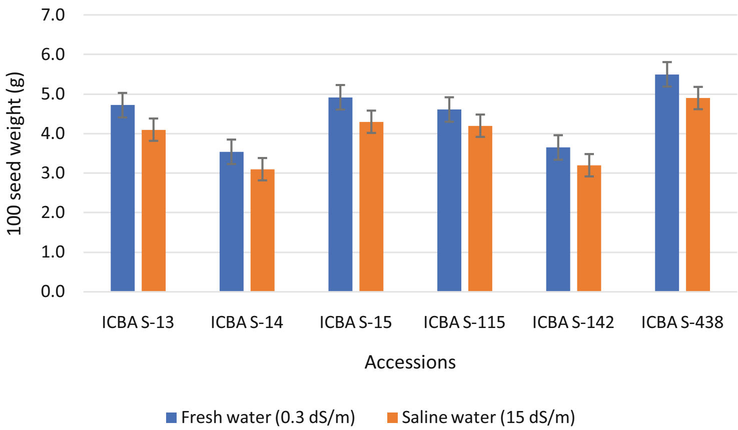

Fig. 12.6 100-seed weight of 6 safflower accessions grown at low and high salinities

size of the crop. Larger safflower seed usually has higher germination vigor but lower oil content (El Saeed 1966). The safflower seed used for bird feeding is generally smaller in size. The study revealed that ICBA S-438 had the maximum weight (5.5 g) for 100-seed compared to the other 5 safflower accessions (Fig. 12.6). On the other hand, ICBA S-14 showed the lowermost weight (3.5 g) for the trait. The difference between the two cultivars is more than 150%. The 100-seed weight shows more variation than other traits among the six safflower cultivars.

The salinity didn't have much negative impact on the trait as it reduced 9–13% of the seed weight of the six accessions. The least effected genotype was ICBA S-115, whereas salinity had the maximum impact on ICBA S-13. The research by Janardhan et al. (1986), Feizi et al. (2010) and Siddiqi et al. (2011) also showed the decrease in 100-seed weight in safflower because of high salinity, while, on the other hand, a slight increase in the seed mass due to salinity was observed by Bassil and Kuffka (2002).

12.3.7 Days to Flowering

Safflower normally is a long-day plant and flowering is started by roughly 14 hours of daylight; however high temperature quickens the process (Oyen and Umali 2007). The results indicate that for the two accessions ICBA S-14 and ICBA S-15, days to flowering were 85 (Fig. 12.7). On the other hand, ICBA S-115 and ICBA S-14 flowered within the shortest period of time (75 days). The early flowering safflower cultivars are better for cut flower market. Hence these two cultivars can be used for floriculture as they flower within a short period of time.

The study demonstrates that flowering was accelerated by salty water treatment in all the six safflower accessions (Fig. 12.7). Majority of the genotypes show three days early flowering in the high saline water treatment, while ICBA S-15 and ICBA S-142 flowered 2 days earlier than the control. Early flowering may be beneficial for the farmers who are engaged in floriculture business of safflower. Francois et al. (1964) also found decrease in number of days to flowering due to salinity in safflower.

12.3.8 Petal Life

Apart from flower color and spinelessness, petal life of safflower is another trait to assess the suitability of a cultivar for floriculture. The genotypes with longer petal life are more suitable for floral industry. The results demonstrated that petals of

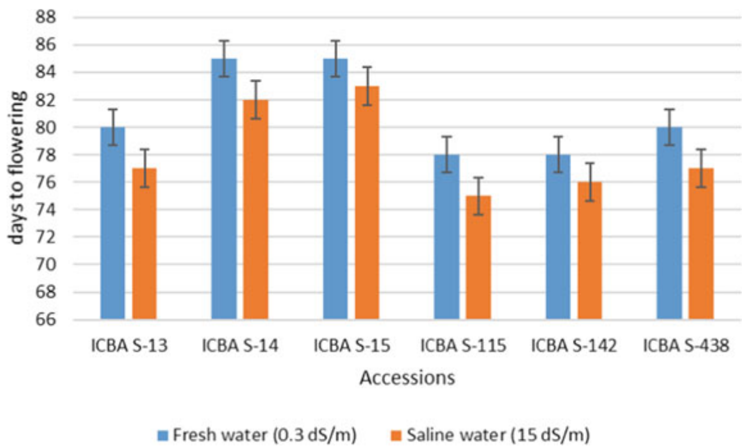

Fig. 12.7 Days to flowering of 6 safflower genotypes at two salinities

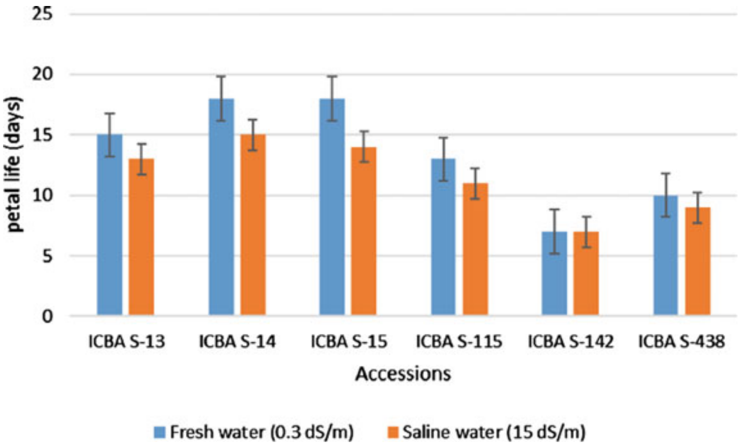

Fig. 12.8 Petal life of 6 safflower genotypes at high and low salinities

ICBA S-14 and ICBA S-15 had the longest life as they last for 18 days (Fig. 12.8). On the other hand, the petals of ICBA S-142 remained fresh for just 7 days. The safflower genotypes with longer petal life are more suitable for cut flower markets compared to others.

The high salinity had no effect on petal life of ICBA S-142, while it was shortened by 4 days in ICBA S-15 (Fig. 12.8). On average, decline in petal life of the safflower accessions due to salinity is around 13%. Reduced petal life may help those famers who sell the dried flowers of the crop for dye and medicinal purposes to bring the produce to the market earlier.

12.4 Conclusion

The study of six safflower cultivars at low and high salinities reveals that safflower can be grown in salt affected areas or the regions where only saline water is available for crop irrigation. High salinity (15.2 dS/m) treatment reduces the seed yield on average by 23% and plant height by 21% in comparison with the control. The impact of salinity on both traits is quite bearable under such harsh conditions. In the marginal lands where traditional crops cannot be cultivated because of salinity, safflower can provide livelihood to the farmers as it has the potential to be grown as an oil seed, floriculture and fodder crop.

References

Bassil ES, Kuffka SR (2002) Response of safflower (*Carthamus tinctorius* L.) to saline soils and irrigation: II. Crop response to salinity. Agric Water Manag 54:81–92

Bradley VL, Guenthner RL, Johnson RC, Hannan RM (1999) Evaluation of safflower germplasm for ornamental use. In: Janick J (ed) Perspectives on new crops and new uses. ASHS Press, Alexandria, VA, pp 433–435

Chevallier A (1996) Encyclopedia of medicinal plants. Dorling Kindersley Publishers, London

El Saeed E-AK (1966) Effects of seed size on oil content and seedling emergence in safflower (*Carthamus tinctorius* L.) grown in Sudan. Exp Agric 2:299–304

Feizi M, Hajabbasi MA, Mostafazadeh-Fard B (2010) Saline irrigation water management strategies for better yield of safflower (*Carthamus tinctorius* L.) in an arid region. AJCS 4(6):408–414

Francois LE, Yermanos DM, Bernstein L (1964) Salt tolerance of safflower. Calif Agric 18 (9):12–14

Harlan J (1992) Crops and man, 2nd edn. ASA, CSSA, Inc, Madison, WI, 284 pp

Heuzé V, Tran G (2017) Safflower (*Carthamus tinctorius*) forage. Feedipedia, a programme by INRA, CIRAD, AFZ and FAO. http://www.feedipedia.org/node/173

Irving DW, Shannon MC, Breda VA, Mackey BE (1988) Salinity effects on yield and oil quality of high-linoleate and high-oleate cultivars of safflower (*Carthamus tinctorius* L.). *J Agric Food Chem* 3:37–42

Janardhan KV, Patil BN, Raiker DS (1986) Relative tolerance of safflower (*Carthamus tinctorius* L.) varieties to saline water irrigation. Indian J Plant Physiol 24(2):118–124

Jaradat AA, Shahid M (2006) Population and multilocus isozyme structures in a barley landrace. Plant Genet Resour-C 4(2):108–116

Kaya MD, Ipek A, Ozturk A (2003) Effects of different soil salinity levels on germination and seedling growth of safflower (*Carthamus tinctorius* L.). Turk J Agric 27:221–227

Knowles PF (1989) Safflower. In: Robbelen G, Downey RK, Ashri A (eds) Oil crops of the world. McGraw Hill, New York, pp 363–374

Landau S, Friedman S, Brenner S, Bruckental I, Weinberg ZG, Ashbell G, Hen Y, Dvash L, Leshem Y (2004) The value of safflower (*Carthamus tinctorius*) hay and silage grown under Mediterranean conditions as forage for dairy cattle. Livestock Prod Sci 88:263–271

Lee YC, Oh SW, Chang J, Kim IH (2004) Chemical composition and oxidative stability of safflower oil prepared from safflower seed roasted with different temperatures. Food Chem 84:1–6

Norris LE, Collene AL, Asp ML, Hsu JC, Liu LF, Richardson JR, Li D, Bell D, Osei K, Jackson RD, Belury MA (2009) Comparison of dietary conjugated linoleic acid with safflower oil on body composition in obese postmenopausal women with type 2 diabetes mellitus. Am J Clin Nutr 90(3):468–476

Oelke EA, Oplinger ES, Teynor TM, Putnam DH, Doll JD, Kelling KA, Durgan BR, Noetzel DM (1992) Safflower. Alternative field crop manual. University of Wisconsin, Madison, WI

Oyen LPA, Umali BE (2007) *Carthamus tinctorius* L. Record from protabase. In: van der Vossen HAM, Mkamilo GS (eds) PROTA (Plant Resources of Tropical Africa/Ressources végétales de l'Afrique tropicale), Wageningen, Netherlands

Ramsden CE, Zamora D, Leelarthaepin B, Majchrzak-Hong SF, Faurot KR, Suchindran CM, Ringel A, Davis JM, Hibbeln JR (2013) Use of dietary linoleic acid for secondary prevention of coronary heart disease and death: evaluation of recovered data from the Sydney Diet Heart Study and updated meta-analysis. BMJ 346:e8707

Safavi SM, Pourdad SS, Safavi SA (2013) Evaluation of drought tolerance in safflower (*Carthamus tinctorius* L.) under non-stress and drought stress conditions. Int J Adv Biol Biomed Res 1 (9):1086–1093

Shahid SA, Dakheel AJ, Mufti KA, Shabbir G (2009) Automated in-situ soil salinity logging in irrigated agriculture. Eur J Sci Res 26(2):288–297

Siddiqi EH, Ashraf M, Al-Qurainy F, Akram NA (2011) Salt-induced modulation in inorganic nutrients, antioxidant enzymes, proline content and seed oil composition in safflower (*Carthamus tinctorius* L.). J Sci Food Agric 91:2785–2793

Soil Survey Staff (2010) Keys to soil taxonomy, 11th edn. USDA-NRCS, US. Government Printing Office, Washington, DC

Stanford K, Wallins GL, Lees BM, Mundel HH (2001) Feeding value of immature safflower forage for dairy ewes. Can J Anim Sci 81:289–292

Uter J (2008) Safflower in European floriculture: a review. Proceedings of the 7th international safflower conference, Wagga Wagga, New South Wales

World Production of Safflower Seeds (2015) Browse Production/Crops/World. United Nations Food and Agriculture Organization, Statistics Division (FAOSTAT). Data retrieved April 24, 2017

Yau S-K, Ryan J (2010) Response of rainfed safflower to nitrogen fertilization under Mediterranean conditions. Ind Crop Prod 32:318–323

Zohary D, Hopf M (2000) Domestication of plants in the Old World, 3rd edn. Oxford University Press, New York, p 211

Chapter 13
Jatropha Plantation in Oman

Ahmed Al-Busaidi and Muhtaque Ahmed

Abstract Salinity management of soil and water resources in Oman is highly needed if the agricultural production has to be kept active. Researches in management of saline soils are important to produce different agricultural data under Oman conditions and formulation of future recommendations to different farmers.

Jatropha curcas is biofuel plant that could grow in coarse and fine soils. It could tolerate pests and drought conditions. It produces seeds with 40% of oil. *Jatropha* oil can be a source for a biodiesel that can be used to run cars, whereas the residue can be converted to biomass for power generation.

It was important to test *Jatropha* growth under Oman conditions and evaluate the oil quality for commercial production. Sultan Qaboos University received four kilograms of *Jatropha* seeds from National Biodiversity Authority, National Bureau of Plant Genetic Resources, and Central Salt and Marine Chemicals Research Institute, India.

The study was done to evaluate the ability of *Jatropha* plant to grow under different saline and stress conditions. In addition, the ability of this plant to grow and survive under Oman conditions of water, salinity, and heat stresses was also investigated.

It was found that *Jatropha* plant can survive and grow well under drought and saline stress conditions. *Jatropha* growth under 2 and 4 days irrigation intervals was almost the same, whereas 6 days irrigation intervals gave the lowest growth. However, in some cases, 6 days irrigation intervals gave a good growth as 2 and 4 days irrigation. Succulent stem found in *Jatropha* plant helped in balancing the shortage of water and improved survival rate. The transpiration efficiency and conservation of transpired water improved water productivity. Therefore, they are good indicators for quick establishment of *Jatropha* plant on degraded and un-vegetated lands.

Ability of *Jatropha* plant to grow under heat stress and saline irrigation (3 and 6 dS m^{-1}) conditions was also evaluated. Plants were grown under three

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metrological conditions. The first place was in glasshouse with controlled temperature. The second place was in shade house, and the third one was in open area.

Growth under glasshouse condition was the best even under saline irrigation water of 6 dS m^{-1}. Open field with high temperature (average = 40 °C) showed the worse growth where salts were accumulated in the soil surface. Young *Jatropha* plant could not survive under salinity and heat stress conditions.

Final study was done to evaluate if *Jatropha* plant can grow in a field of unfertile soil using treated wastewater and salty water for irrigation. The growth was very good under all conditions, and treated wastewater gave the best growth.

Keywords Soil salinity · Heat stress · Drought · Biofuel

13.1 Introduction

Conventional water resources of good quality are scarce especially in arid and semiarid regions. The salinization of soils and water is a substantial constraint to crop productivity. Moreover, climate change impact and declining water resources will make it difficult to satisfy food requirements in the future as 70% and in some places 90% of the available water resources is used in food production. To cope with the water shortage, it is necessary to adopt water-saving agricultural countermeasures (Mao et al. 2003). Water conservation and its efficient use in agriculture are becoming increasingly important (Ward and Manuel 2008). Agronomic measures such as varying tillage practices, mulching, and anti-transpirants or drought-tolerant plants can reduce the demand for irrigation water and improve irrigation water use efficiency.

United Nations Environment Program listed the Sultanate of Oman as an acute water-scarce country. The annual rainfall is limited, and average precipitation is only about 75–100 mm (MAF 2007). Perennial streams are nonexistent and renewable water resources are inadequate. Therefore, there is a dire need for the judicious use of water with minimum losses wherever possible.

Jatropha curcas (physic nut) is a biofuel crop that could survive under different growth condition and produce oil up to 40% as biodiesel and solid biomass can be used for power generation (Mandpe et al. 2005; Achten et al. 2008; Azam et al. 2005). Moreover, the organic waste can be digested to for biogas (CH_4) production, whereas the press cake can be used as a fertilizer (Francis et al. 2005).

Therefore, *Jatropha* plantation will not affect food production if *Jatropha* is grown in degraded soil (Maes et al. 2009a). However, unsuitable land does not mean that *Jatropha* will produce significant amounts of oil (Achten et al. 2008). Therefore, investments in this plant could hold environmental and socioeconomic risks (Achten et al. 2007, 2010). However, there is a large-scale expansion in *Jatropha* investments which are ongoing (GEXSI 2008).

However there are no reports on existence of *Jatropha* on saline soils or studies related to salt tolerance either at whole plant or at cell level. Therefore the present study was undertaken to evaluate the responses of *Jatropha* to salt and drought stresses under different environmental conditions to assess the possibility of biofuel production in hot and dry areas. Sharratt (1999) reported that day length and temperature affected *Jatropha* growth parameters. It was reported by Francis et al. (2005) that *Jatropha* grows in areas with extreme climate and soil conditions that could not be inhabited by most of the agriculturally important plant species. Therefore, understanding the effect of water shortage and soil salinity with different growth condition could be useful for the quality production of biofuel plants in semiarid and arid countries. This study was aimed to evaluate the effects of different environmental conditions, salinity, irrigation intervals, and mulch amendment on the salt accumulation and *Jatropha* growth.

13.2 Materials and Methods

Pot experiments were conducted in Agricultural Experiment Station, College of Agricultural and Marine Sciences, Sultan Qaboos University (SQU), Oman, in the following three environments: (1) a glasshouse (G) with controlled temperature (around 23 °C), (2) a shade house (S), and (3) an open area (O). Air temperature and relative humidity were measured in all studied locations. In each location, 32 pots of 10 L size were filled with sandy soil, and organic mulch to a depth of 3 cm was added to 12 of them. Healthy *Jatropha* seedlings were transplanted to all pots of different locations. For irrigation treatments, four pots of control and mulch amended were irrigated every 2, 3, and 4 days continuously. Saline water of 3 and 6 dS m^{-1} was prepared by diluting seawater to reach the desired EC. In each location, four pots were irrigated with saline water of 3 dS m^{-1}, while other four were irrigated with saline water of 6 dS m^{-1}. The water needed was given based on saturation point of the soil, whereas evapo-transpiration was calculated based on the metrological data available in the study area. Doses of NPK liquid fertilizer was added to plant in the irrigation water. Plant leaf area and height were monitored during the experiments. After 4 months, all *Jatropha* plants were harvested, and their heights, leaf area, total fresh weights of green biomass, and roots were taken.

Original soils samples were collected from Oman desert. All samples were air-dried and sieved (<2 mm). Hydrometer method was used for soil texture analysis. Soluble cations were extracted by saturated paste extract. Electrical conductivity (EC) and pH of the soil extract were measured with pH and EC meters. The concentrations of the cations were determined by inductively coupled plasma (ICP, Perkin Elmer, Optima 3300 DV) machine. The physicochemical properties of the soil are given in Table 13.1

Data were analyzed statistically using the analysis of variance, and the means were compared at the probability level of 5% using least significant difference (LSD).

Table 13.1 Physicochemical properties of the used soil and waters[a]

Media	EC	pH	Na	Mg	Ca	K	Fe	Zn	Cu	B
	dS m^{-1}	–				mg L^{-1}				
Sandy soil	0.27	8.18	63.19	37.82	60.02	30.45	0.02	0.07	0.01	0.17
Fresh water	0.15	8.00	53.30	6.46	22.20	5.28	0.02	0.04	0.007	0.18
EC_{w3}	3.01	8.28	465.0	48.70	55.20	26.50	0.03	0.04	0.002	0.96
EC_{w6}	6.01	7.91	752.0	62.70	74.40	27.30	0.02	0.04	0.004	0.77

[a]In all samples the concentrations of Mn, Pb, Cr, Cd, and Ni were less than 0.001 mgL^{-1}

13.3 Results and Discussion

13.3.1 Soil and Irrigation Water Quality

Soil is the supporting media for plant growth, and the quality of the soil could affect water and nutrient availability, whereas water shortage could kill the plant or affect its growth parameters. Table 13.1 provides data on physiochemical properties of the used soils and waters. The used sandy soil is considered a suitable media for plant growth. It has some nutrients, acceptable value of pH, almost free of salts, enhancing leaching process and root elongation. Most of the plants prefer sandy soil with good aeration and less possibility to be affected by salt accumulation when irrigated with saline water. However, low water holding capacity is the main problem with coarse textured soils which can be solved by amending the soil with suitable materials such as organic mulch.

Fresh water gave the best plant growth, but limitation of fresh water is forcing scientists toward saving methods and application of salty water. Irrigation with salty water will add extra salts to the growing field. However, in sodic conditions, salty water improves water movements through soil profile and may add some needed nutrients to the soil (Table 13.1). High infiltration rate of sandy soils supports the idea of saline irrigation for salt-tolerant plants. The behavior of different plants to salts depends on concentration of salts, ion types, growth conditions, and plant age, whereas element uptake by plants growing in salty soil depends on (1) nutrient activity, which depends upon concentration, pH, composition, and pE, (2) concentration of the elements that influence the absorbance of this nutrient by roots, and (3) different factors in the environment (Pessarakli 1999). However, *Jatropha* can grow in a wide range of soils especially coarse sandy soils (Heller 1996; Foidl et al. 1996), whereas very fine soils could restrict the growth of *Jatropha* roots (Singh et al. 2006; Biswas et al. 2006; Heller 1996). The soil surface slope should not exceed 30° (Tewari 2007), and depth of soil should be at least 45 cm (Gour 2006). *Jatropha* required low nutrients with pH value of less than 9 (Tewari 2007; Biswas et al. 2006). However, good amounts of nutrients are needed to support the productivity of the plant (Foidl et al. 1996). Generally, the best soils for *Jatropha* are aerated sands and loams of at least 45 cm depth (Gour 2006). Ability to grow in alkaline soils has been widely reported, but the soil pH should be within 6.0 to 8.0/ 8.5 (FACT 2006). There is evidence from northwest India that *Jatropha* is tolerant of saline irrigation water, although yield under these conditions is not documented (Dagar et al. 2006).

13.3.1.1 Growth Conditions

The meteorological data recorded during the study is given in Fig. 13.1. In the glasshouse, the plants were grown at almost constant temperature (23 °C), whereas in shade house and open area the temperature (Temp) was very high (max>40 °C). The temperature values were remarkably differed among the places in the order of open area > shade house > glasshouse. Open area and shade house almost got similar temperature, but the big difference was in solar radiation (SR) in which open area got the highest value and that led to heat stress condition. Relative humidity (RH) was between 50 and 65% for all three locations and was not a limiting factor for plant growth.

Jatropha can survive in semiarid environments and adapt with dry seasons, whereas humid conditions with average temperatures between 20 °C and 28 °C and rainfall range between 250 mm and 3000 mm lead to better crop growth (Foidl et al. 1996; Heller 1996; Gour 2006; Makkar et al. 2007). Baumgaart (2007) reported that *Jatropha curcas* needs a tropical climate to grow in. The ideal temperature would be between 20 and 40 °C. The plant is well adapted to conditions of high light intensity (Baumgaart 2007; Jongschaap et al. 2007) and is unsuited to growing in shade.

Evapo-transpiration is dependent on growing conditions, water availability, and salinity treatments. Based on metrological data shown in Fig. 13.1, open area showed the highest value of evapo-transpiration followed by the shade house and glasshouse (Fig. 13.2). This order could be due to the constant temperature conditions in the glasshouse. The moderate and suitable temperature of glasshouse was unable to expedite evapo-transpiration rate, whereas the high temperature in shade house accelerated water loss and increased evapo-transpiration. The interaction of

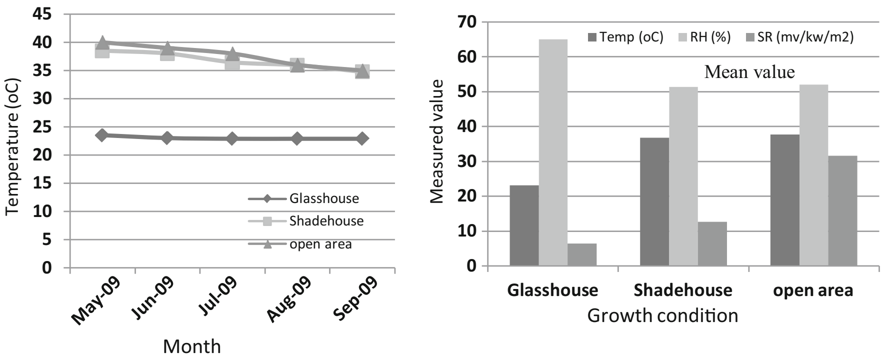

Fig. 13.1 Average meteorological data of three experimental sites

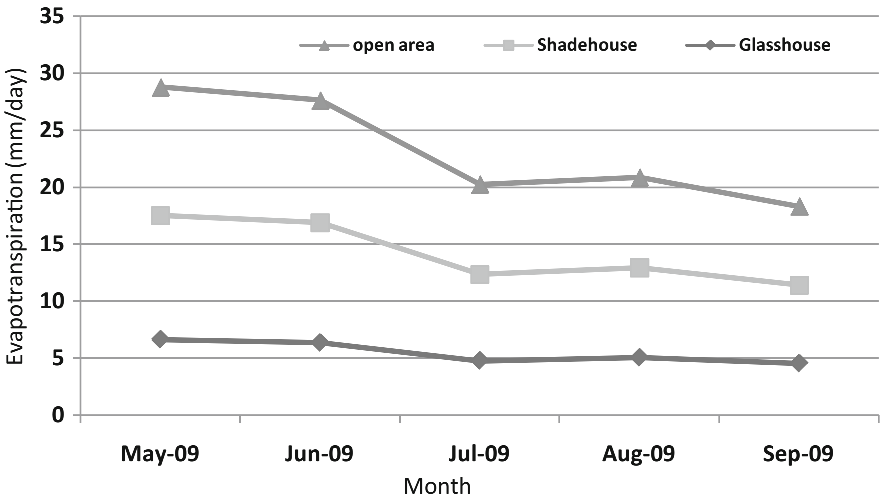

Fig. 13.2 Evapo-transpiration as affected by different growth condition

high temperature, solar radiation, and wind speed in the open area were the main reasons in increasing the evapo-transpiration of *Jatropha* plant. The evapo-transpiration and other soil parameters were differentiated mainly due to metrological differences of the experimental sites. Plants substantially enhanced evapo-transpiration at the peak growth stage. Heat intensity along with the growing stage of plants tremendously affected evapo-transpiration rate and salt accumulation in the soils irrespective of the salt treatments.

Transpirational water flow and root selectivity provide the net uptake of water and salts (Yeo 1999). Salt transport in plants can be controlled by greater mass flow of solution through higher magnitude of evapo-transpiration or soil-root interface. Therefore, salts could accumulate and kill the plants in hot climate.

There is little quantitative data available on the water needs, water productivity, and water-use efficiency of *Jatropha*. The data for water use over 2-year study found the actual evapo-transpiration for non-stressed *Jatropha* plants is 42–57% of calculated evapo-transpiration (Wani and Sreedevi 2007).

The average data used in Fig. 13.1 reflected the combined effect of all possible parameters that could affect evapo-transpiration process including salt content of the irrigation water. Evapo-transpiration was positively related to the quality of irrigation water (Fig. 13.3). Reduced bioavailability of water and retarded plant growth under saline irrigation produced a poor evapo-transpiration in the system (Fig. 13.4). This effect was also reported by Koszanski and Karczmarczyk (1985), Abdul et al. (1988), and Heakal et al. (1990). Plant growth can be reduced in saline soils through reduced metabolic activities due to salt toxicity, reduced water absorption, and nutrient deficiency caused by ionic interferences (Yeo 1983). As shown in Fig. 13.3, saline irrigation inhibited evaporation from the soil surface. It could happen due to enhanced water viscosity, density, and chemical bonds in the

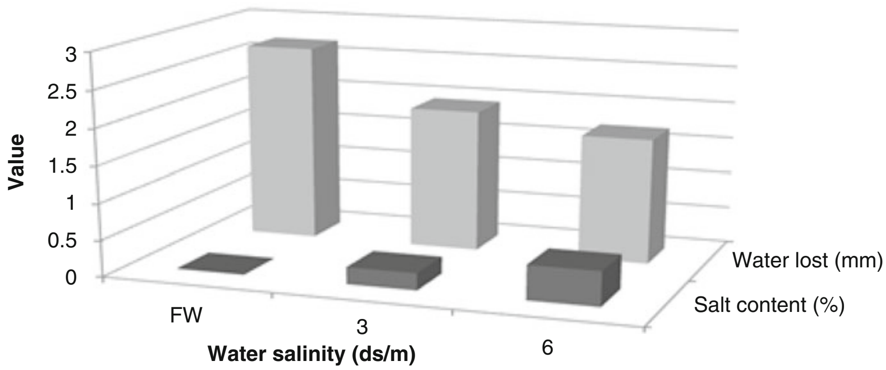

Fig. 13.3 Salt concentration and water loss as affected by saline water treatments

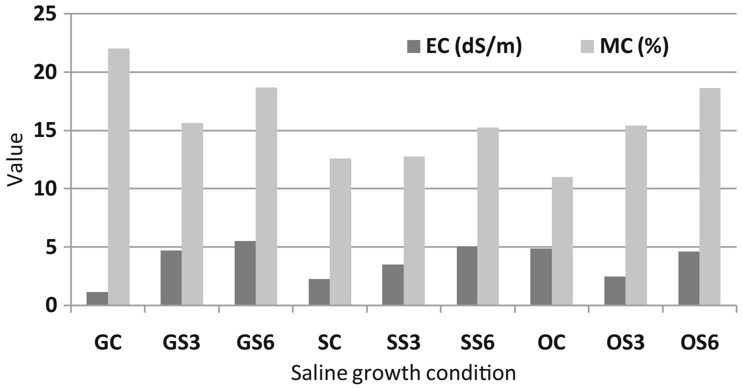

Fig. 13.4 Salt accumulation under different environments (GC, glasshouse control; GS3, glasshouse salinity 3dS/m; GS6, glasshouse salinity 6dS/m; SC, shade house control; SS3, shade house salinity 3dS/m; SS6, shade house salinity 6dS/m; OC, open area control; OS3, open area salinity 3dS/m; OS6, open area salinity 6dS/m)

soil-salt system. Moreover salt crusts formation could also reduce soil evaporation. Richards et al. (1998) reported that weather temperature, water density, and salinity affected several water characteristics, e.g., evaporation, etc. Earlier Al-Busaidi and Cookson (2005) also reported salt crust formation on the soil surface due to saline irrigation, which inhibited evaporation and reduced leaching efficiency.

As expected, salt accumulation in soil was affected positively by saline irrigation (Fig. 13.4). Higher salt treatment gave higher values of salt accumulation in all growing conditions. However, high temperature in the shade house and open area should give the highest values for salt accumulation, but due to high water consumption, continuous saline irrigation, and high water content in the glasshouse, the soil salinity gave almost similar value to the saline irrigation water. Moreover, all treatments were showing the same phenomena of high soil water content (MC) under saline irrigation as it was shown in Fig. 13.3.

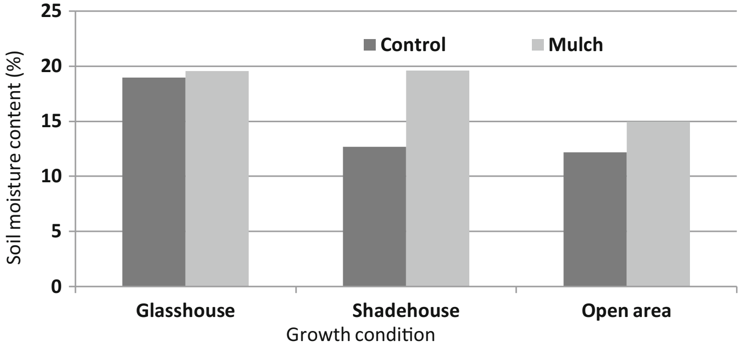

Fig. 13.5 Soil water content as affected by mulch application

Salt accumulation in soil usually related to soil evaporation and water uptake by plants (Ben-Hur et al. 2001; Bresler et al. 1982). Linear soil salinity with the application of saline water down the soil profile was reported by Blanco and Folegatti (2002), whereas Petersen (1996) found low soil salinity with increased volume of irrigation water.

Coarse-textured soil usually has low ability to hold water compared to fine textured soil. Therefore, amending sandy soil with environment friendly mulch such as wood or organic mulch will maintain high amount of water, reduce irrigation amount, and encourage plant growth, which is clearly seen in Fig. 13.5. Mulch amended treatments held more water compared to control. The extra water was used to cool the surrounding environment and support salt leaching process and was a source of water for plant growth, whereas in control treatment, the plant suffered from water shortage and high temperature and was stressed due to the inability of sandy soil to hold water for a long time. It was found by Costa and Gianquinto (2002) that total fresh weight of bell pepper fruit was reduced due to water stress condition, whereas Gouranga Kar and Ashwani Kumara (2007) reported that moisture content of the soil was improved with mulch application.

Ajmer et al. (2007) investigated the effect of wheat straw mulch on soil temperature. They reported that wheat straw mulching substantially lowered the maximum soil temperature at seeding depth. Maximum soil temperatures in unmulched plots ranged from 32.2 to 44.4 °C in channel and 31.6 to 46.4 °C in flat sown maize. Mulching lowered soil temperatures by 0.8–7.0 °C in channel and 0–9.9 °C in flat-sown maize. Al-Wahaibi et al. (2007) reported that the soil moisture values were significantly higher in mulched treatments of any material as compared with no mulching (control).

13.3.1.2 Plant Parameters

Water, heat, and salinity stresses are main factors affecting plant growth in dry lands. *Jatropha* growth was significantly affected by saline irrigation, mulch amendment,

Table 13.2 Plant growth parameters as affected by different growth factors

Growth condition	Green biomass (g)	Root weight (g)	Total plant weight (g)	Plant height (cm)	Leaf area (cm^2)
GC	257.44c	38.56d	296.01c	77.11c	117.85b
GM	362.67b	49.11c	411.78b	95.56b	164.90a
G3&6	436.00a	86.17a	522.17a	114.17a	131.39c
SC	105.22f	12.56g	117.78f	70.33e	44.61f
SM	139.33e	13.89f	153.23e	64.89f	56.66e
S3&6	157.17d	20.17e	177.34d	74.17d	70.51d
OC	36.44h	61.44b	97.89g	26.56h	9.33i
OM	20.50i	5.67i	26.17i	26.75g	15.14g
O3&6	44.92g	8.08h	53.01h	26.50i	11.59h

Note: The mean values in the column with the same alphabets indicate nonsignificant difference according to Duncan's multiple range test at $P < 0.05$. *GC* glasshouse control, *GM* glasshouse mulch, *G3&6* glasshouse salinity 3 & 6dS/m, *SC* shade house control, *SM* shade house mulch, *S3&6* shade house salinity 3 & 6dS/m, *OC* open area control, *OM* open area mulch, *O3&6* open area salinity 3 & 6dS/m

and growth conditions (Table 13.2). The favorable condition of the glasshouse gave the highest yield followed by shade house and lastly by open area. Mulch addition normally gave better performance as compared to control. It seems that *Jatropha* plant can tolerate salinity of 6 dS m^{-1} and soil salinity was not high enough to suppress plant growth parameters (qualify by saying it only for the duration of study). Treatment with saline water gave higher biomass production as compared to the fresh water. In all growth conditions, salinity treatments gave the best plant parameters compared to other treatments. Perhaps low level of salts was a source of nutrient for the plant and was inhibiting evaporation process and improving the growth conditions. Moreover, sandy soil is a good media to leach the salts and release any salinity stress.

Sharma et al. (2008) and Maes et al. (2009) reported that *Jatropha curcas* plant does not need much water. It is a strong plant that can be irrigated with diluted seawater. It grows well with a saline concentration of 11.6 dS m^{-1}. Seawater has a saline concentration of approximately 55 dS m^{-1}. If the rainy season is good, the water can be stored and used for irrigation, whereas in other study, it was found that *Jatropha* irrigated with saline water equal to 3.0 dS m^{-1} had plant height, stem diameter, number of leaves, and leaf area reduced by 9.07, 17.63, 23.41, and 42.58%, respectively (Aparecida et al. 2009).

Plant could tolerate salts if (1) damage can be prevented, (2) plant growth can be stabilized, and (3) plant continuously growing (Zhu 2001). Salts could damage plant cellular system (Zhu et al. 1997; Serrano et al. 1999); therefore, plant growth and survival depends on plant adaptations through osmoregulation (Elkahoui et al. 2005; Niknam et al. 2006; Cherian and Reddy 2003). In addition, plant responds with physiological and biochemical changes (Niknam et al. 2006; Cherian and Reddy 2003; Lutts et al. 1996; Elkahoui et al. 2005). These changes aim at retention of

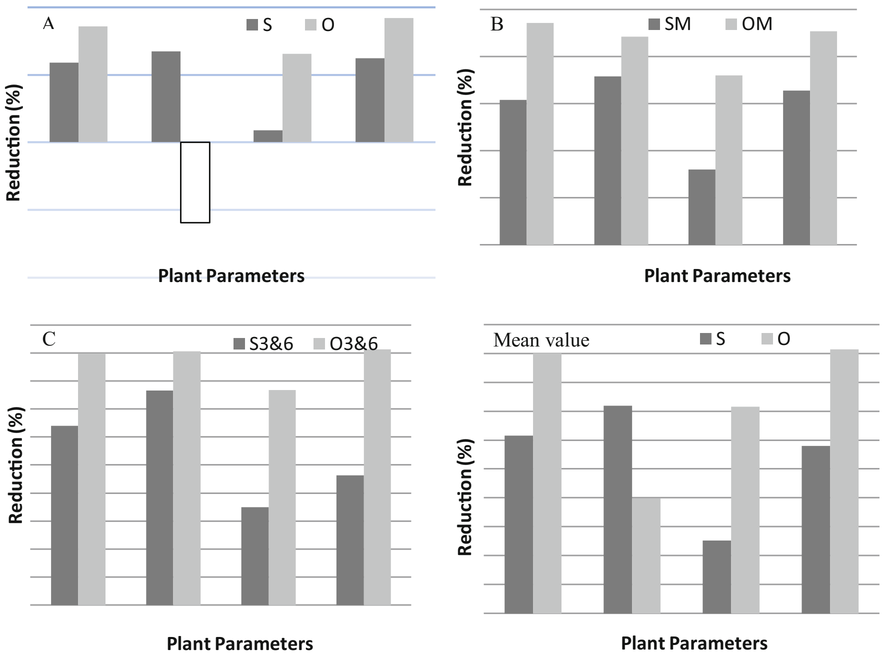

Fig. 13.6 Reduction in plant growth parameters compared to growth in glasshouse

water in spite of high external osmoticum and maintenance of metabolic activities (Hasegawa et al. 2000).

Comparing all data together, it seems that growth condition was the main factor controlling *Jatropha* growth. The good conditions of glasshouse gave the best result, whereas plant in the open area was suffering mostly from the heat stress. There was significant reduction in plant parameters under shade house and open area compared to the glasshouse which is clearly seen in Fig. 13.6. In Fig. 13.6a, it can be seen that when the plant cannot produce green biomass, the efforts of survival will go to the root side, and this is why there was a good growth in root biomass of open area compared to the glasshouse root weight. In other treatments of Fig. 13.6b, c, the availability of water either by mulch amendment or saline irrigation enhanced green biomass, but due to heat stress, there was a big reduction (ca. 50%) in plant growth parameters compared to the glasshouse. It is clear that environmental growth condition was the main reason for all reductions in plant growth parameters and that was clearly seen by mean values of plant growth parameters of different sites (Fig. 13.6).

Growth condition with high temperature was the main stress for *Jatropha* growth. Several reports were published for the effect environmental conditions on plant growth (Sule et al. 2004; Marmiroli et al. 1989; Sharratt 1999; Saarikko and Carter 1996). This study also confirmed that growth conditions affected *Jatropha* performance under the same type of irrigation water. The effect of salts and water stress with high temperature could lead to higher loss in plant yield (Daoud et al. 2001).

13.3.2 Effect of Irrigation Intervals and Mulch Application

It has been reported that plant-water relations of stem succulents do not change with age, as stem-succulent species do not avoid drought stress through a better access to soil water (they generally have shallow rooting systems), but through their stem water reserves (Borchert 1994). *Jatropha* is one of the succulent species that can survive under drought conditions. In this study, water-related aspects such as irrigation intervals and mulch application were found to have a significant effect when the plant was affected by heat stress. At the same time when more water was given to the plant, better green biomass was produced, but this is not true all the times. From Fig. 13.7, it can be seen that growth parameters in glasshouse were not highly affected by irrigation intervals and mulch application. The plants were grown in conditions where there was no heat stress or drought stress due to high evapo-transpiration. However, control treatment of 3-day irrigation intervals was better in growth than 2 days intervals which could be explained by the ecology of *Jatropha* which dislikes the wet land conditions. In shade house, close intervals of irrigation water was also found as not the best option for *Jatropha* growth which means that *Jatropha* is mostly adapted to drought conditions, and it can grow better in highly aerated soil. Although *Jatropha* has been observed growing with 3000 mm of rainfall (Achten et al. 2008; Foidl et al. 1996), higher precipitation is likely to cause fungal attack and restrict root growth in all but the mostly well-drained soils. *Jatropha* is not found in the more humid parts of its area of origin, Central America and Mexico (Achten et al. 2007).

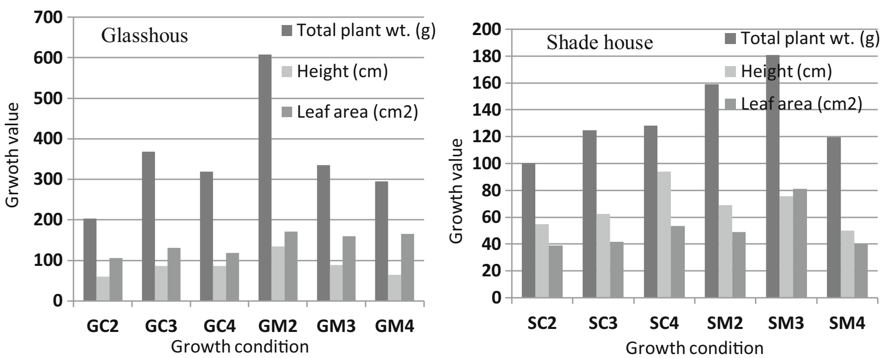

Fig. 13.7 Plant parameters as affected by irrigation intervals and mulch amendment

Table 13.3 Summary of two-way analysis of variance on growth condition, mulch amendment, irrigation intervals, and saline water effect on soil and plant parameters

Parameter	Growth condition (G)	Mulch application (M)	Irrigation intervals (I)	Saline water (S)	G*M*I*S
	Significance				
Soil MC	S	S	S	S	S
Soil EC	S	S	S	S	S
Plant weight	S	S	S	S	S
Plant height	S	S	S	S	S
Leaf area	S	S	S	S	S

In shade house, there was heat stress, and plant was subjected to high evapo-transpiration. Therefore, it can be seen that mulch application positively affected plant growth by reducing evapo-transpiration, increasing soil moisture, and decreasing soil temperature. Jiangtao et al. (2006) found that rice straw mulching decreased evapo-transpiration by 33% and 63% (in 2003) and 36.5% and 57.1% (in 2004) to control treatment. Moreover, Mark and Gregory (1998) found that organic mulches improved soil moisture and reduced soil temperature. In addition, Earlier Gicheru et al. (2006) reported that surface mulched and manure applications reduced soil infiltration rates and gave higher soil moisture content compared to control. The same findings were confirmed by Ramakrishna et al. (2006). Jemison and Chris (2004) illustrated that when short paper fiber residuals were used as surface mulch, significantly higher amounts of moisture was observed in the soil at each sampling date indicating that the material does reduce evaporative loss, whereas Ajmer et al. (2007) reported that mulching, on an average, improved maize leaf area index by 0.42, plant height by 14 cm, grain yield by 0.24 t ha^{-1}, and biomass by 1.57 t ha^{-1}. Buerkert et al. (2000) reported that their results showed crop residues induced total dry matter increased in cereals up to 73%.

Usually growth conditions are the main factor controlling soil and plant parameters. It can be seen from Table 13.3 that all applied treatments significantly affected soil and plant growth parameters. However, it can be seen from data that growth condition was the main factor that was controlling all other parameters. For example, without heat stress, the evapo-transpiration will be low, and soil moisture will be high, and the possibility of having salinity problem will be low. Moreover, succulent stem of *Jatropha* supported the balance between water lost and gained in plant system. Plant growth and improvement in water productivity, transpiration rate, and efficiency are promising parameters for good growth of this plant in unfertile soil. However, more research is needed to confirm the finding and study the best growth condition under drought and salinity stresses.

Finally, it was observed that *Jatropha* plant can grow under saline (6 dS m^{-1}) and drought stress conditions, but the plant should be transplanted or initiated in winter season or when the average temperature is around 30 °C. The best plants from this study were transplanted to the field. They adapted themselves and tolerated the

Fig. 13.8 Growth of *Jatropha* after transplanting

summer temperature of more than 45 °C. They are growing well and producing seeds (Fig. 13.8).

Last part of this project was to evaluate the ability of *Jatropha* plant to grow in wasteland using saline and treated waste waters for irrigation with addition of organic and inorganic fertilizers. The land was rocky with high salt content, so if *Jatropha* can grow in this soil, that will improve the soil physiochemical properties. Moreover, using treated wastewater for agriculture will add some nutrients and release the pressure on freshwater resources, so it can be saved for other applications.

Wasteland in Agricultural Experiment Station, College of Agricultural and Marine Sciences, Sultan Qaboos University (SQU), was divided to 45 plots and planted with *Jatropha* seedlings. The plots were divided into three lines. Each line was irrigated either with fresh water or treated waste water or saline water with EC of 3 dS m^{-1}. Within each irrigation treatment, known amount of organic or inorganic or mix of both fertilizers was added to each plot.

Data showed that plants irrigated with treated wastewater gave the best growth in terms of plant height and green yield. However, plant growth under saline water was also good. Addition of mix fertilizers (organic and inorganic) gave the best results in which the plant was using the benefit of fast release of nutrients from inorganic fertilizer and the slow release of nutrients from organic fertilizer (Figs. 13.9 and 13.10).

13.4 Conclusion

The present study investigated the possibility of growing *Jatropha* in dry and hot areas. It was found that heat stress was the main factor restricting initial growth of *Jatropha*. It was difficult for the young *Jatropha* plants to grow under heat and salinity stress conditions. However, the plants showed some strength, and they did not die completely. *Jatropha* tolerated soil salinity of up to 6 dS m^{-1}, and in most

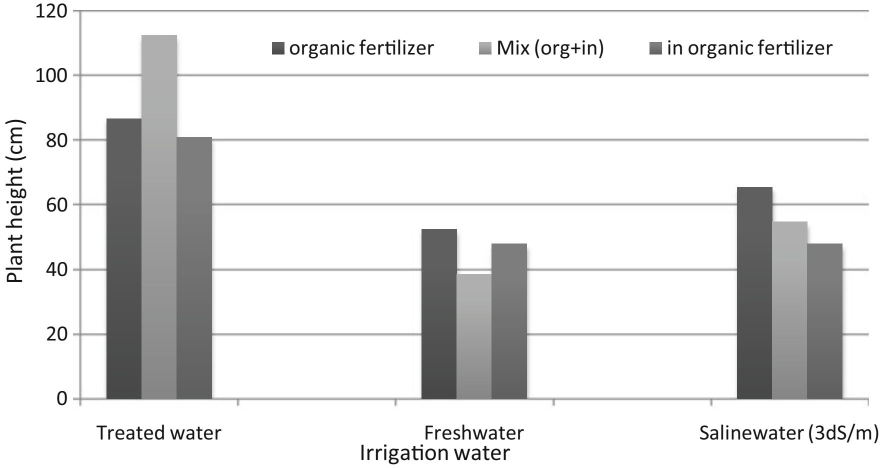

Fig. 13.9 Growth of *Jatropha* in wasteland (rocky and saline) irrigated with treated wastewater, fresh water, and saline water (3 dS m^{-1})

Fig. 13.10 Photos for *Jatropha* growth in wasteland (rocky and saline) irrigated with treated wastewater, fresh water, and saline water (3 dS m^{-1})

cases plant growth parameters were as good as or better than control and mulch treatments. If the meteorological condition is good, the plant can adapt with drought and salinity stresses conditions. However, a good management of drought and salinity stresses is a necessary prerequisite for sustainable agriculture in arid and semiarid areas. Therefore, in hot and dry areas, it is recommended that *Jatropha* plant should be transplanted when temperature is around 30 °C, so the plant will have sufficient time to grow and tolerate future abiotic stresses and produce seeds for biofuel production.

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References

Abdul KS, Alkam FM, Jamal MA (1988) Effects of different salinity levels on vegetative growth, yield and its components in barley. ZANCO 1:21–32

Achten WMJ, Mathijs E, Verchot L, Singh VP, Aerts R, Muys B (2007) Jatropha biodiesel fueling sustainability? Biofuels Bioprod Biorefin 1:283–291

Achten WMJ, Verchot L, Franken YJ, Mathijs E, Singh VP, Aerts R, Muys B (2008) Jatropha bio-diesel production and use. Biomass Bioenergy 32:1063–1084

Achten WMJ, Maes WH, Aerts R, Verchot L, Trabucco A, Mathijs E, Singh VP, Muys B (2010) Jatropha: from global hype to local opportunity. J Arid Environ 74:164–165

Ajmer SS, Nirmal KS, Sukhwinder ST, Gurdev SH (2007) Soil temperature, growth and yield of maize (Zea mays L.) as affected by wheat straw mulch. Arch Agron Soil Sci 53:95–102

Al-Busaidi A, Cookson P (2005) Leaching potential of sea water. J Sci Res Agric Mar Sci 9:27–30

Al-Wahaibi NS, Hussain N, Al-Rawahi SA (2007) Mulching for sustainable use of saline water to grow tomato in Sultanate of Oman. Sci Int (Lahore) 19:79–81

Aparecida RN, Luis NR, Maria BRS, Pedro DF, Lúcia HGC, José Dantas N, Hans RG (2009) Growth of Jatropha irrigated with saline water in greenhouse. Rev Bras Eng Agríc Ambient 13:551–558

Azam MM, Waris A, Nahar NM (2005) Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass Bioenergy 29:293–302

Baumgaart S (2007) Jatropha cultivation Belize. Expert seminar on Jatropha curcas L. agronomy and genetic. 26–28 march 2007. Wageningen, the Netherland, Published by FACT Foundation

Ben-Hur M, Li FH, Keren R, Ravina I, Shalit G (2001) Water and salt distribution in a field irrigated with marginal water under high water table conditions. Soil Sci Soc Am J 65:191–198

Biswas S, Kaushik N, Srikanth G (2006) Biodiesel: technology and business opportunities – an insight. In: Proceedings of the biodiesel conference toward energy independance – focus of Jatropha, Hyderabad, India, June 9–10, 2006, pp 303–330

Blanco FF, Folegatti MV (2002) Salt accumulation and distribution in a greenhouse soil as affected by salinity of irrigation water and leaching management. Revista brasileira de engenharia agricola e ambiental 6:414–419

Borchert R (1994) Soil and stem water storage determine phenology and distribution of tropical dry forest trees. Ecology 75:1437–1449

Bresler E, McNeal BL, Carter DL (1982) Saline and sodic soils: principles-dynamics-modeling. Springer, Berlin, p 236

Buerkert A, Andre B, Komlan D (2000) Mechanisms of residue mulch-induced cereal growth increases in West Africa. Soil Sci Soc Am J 64:346–358

Cherian S, Reddy MP (2003) Evaluation of NaCl tolerance in callus cultures of Suaeda nudiflora Moq. Biol Plant 46:193–198

Costa LD, Gianquinto G (2002) Water stress and watertable depth influence yield, water use efficiency, and nitrogen recovery in bell pepper: lysimeter studies. Aust J Agric Res 53:201–210

Dagar JC, Tomar OS, Kumar Y, Bhagwan H, Yadav RK, Tyagi K (2006) Performance of some under-explored crops under saline irrigation in a semiarid climate in North India. Land Degrad 17:285–299

Daoud S, Harrouni MC, Bengueddour R (2001) Biomass production and ion composition of some halophytes irrigated with different seawater dilutions. First international conference on saltwater intrusion and coastal aquifers-monitoring, modeling, and management. Essaouira, Morocco

Elkahoui S, Hernandez JA, Abdelly C, Ghrir R, Limam F (2005) Effects of salt on lipid peroxidation and antioxidant enzyme activities of Catharanthus roseus suspension cells. Plant Sci 168:607–613

FACT Foundation (2006) Jatropha handbook. FACT Foundation, Eindhoven. http://tinyurl.com/mttvrn

Foidl N, Foidl G, Sanchez M, Mittelbach M, Hackel S (1996) Jatropha curcas L. as a source for the production of biofuel in Nicaragua. Bioresour Technol 58:77–82

Francis G, Edinger R, Becker K (2005) A concept for simultaneous waste land reclamation, fuel production, and socio-economic development in degraded areas in India: need, potential and perspectives of Jatropha plantations. Nat Res Forum 29:12–24

GEXSI (2008) Global market study on Jatropha – final report. GEXSI LLP, Berlin

Gicheru PT, Gachene CKK, Mbuvi JP (2006) Effects of soil management practices and tillage systems on soil moisture conservation and maize yield on a sandy loam in semiarid Kenya. J Sustain Agric 27:1044–1046

Gour VK (2006) Production practices including post-harvest management of Jatropha curcas. In: Proceedings of the biodiesel conference toward energy independance – focus of Jatropha, Hyderabad, India, June 9–10, pp. 223–251

Gouranga K, Ashwani K (2007) Effects of irrigation and straw mulch on water use and tuber yield of potato in eastern India. Agric Water Manag 94:109–116

Hasegawa PM, Bressan RA, Zhu JK, Bohnert HJ (2000) Plant cellular and molecular responses to high salinity. Annu Rev Plant Physiol Plant Mol Biol 51:463–499

Heakal MS, Modaihsh AS, Mashhady AS, Metwally AI (1990) Combined effects of leaching fraction of salinity and potassium content of waters on growth and water use efficiency of wheat and barley. Plant Soil 125:177–184

Heller J (1996) Physic nut – Jatropha curcas L. – promoting the conservation and use of underutilized and neglected crops. PhD dissertation Institute of Plant Genetic and Crop Plant Research, Gatersleben, Germany & International Plant Genetic Resource Institute, Rome

Jemison JM, Chris RH (2004) Use of short paper fiber residuals as soil conditioners. The University of Maine Cooperative Extension

Jiangtao Q, Feng H, Bin Z, Zhenggui W, Huixin L (2006) Role of straw mulching in non-continuously flooded rice cultivation. Agric Water Manag 83:252–260

Jongschaap REE, Corré WJ, Bindraban PS, Brandenburg WA (2007) Claims and facts on Jatropha curcas L. Plant Research International B.V., Wageningen

Koszanski Z, Karczmarczyk S (1985) Use of saline water for irrigation of spring barley and oats. Zeszyty-Naukowi-Akademii-Rolniczej-w-Szczecinie, -Rolnictwo 36: 95–105

Lutts S, Kinet JM, Bouharmont J (1996) Effects of salt stress on growth, mineral nutrition and proline accumulation in relation to osmotic adjustment in rice (Oryza sativa L.) cultivars differing in salinity resistance. Plant Growth Regul 19:207–218

Maes WH, Trabucco A, Achten WMJ, Muys B (2009) Climatic growing conditions of Jatropha curcas L. Biomass Bioenergy 33:1481–1485

Maes WH, Achten WMJ, Reubens B, Raes D, Samson R, Muys B (2009a) Plant-water relationships and growth strategies of Jatropha curcas L. seedlings under different levels of drought stress. J Arid Environ 73:877–884

Makkar HPS, Francis G, Becker K (2007) Bioactivity of phytochemicals in some lesser-known plants and their effects and potential applications in livestock and aquaculture production systems. Animal 1:1371–1391

Mandpe S, Kadlaskar S, Degen W, Keppeler S (2005) On road testing of advanced common rail diesel vehicles with biodiesel from the Jatropha Curcas. Plant Soc Automot Eng 26:356–364

Mao X, Liu M, Wang X, Liu C, Hou Z, Shi J (2003) Effects of deficit irrigation on yield and water use of greenhouse grown cucumber in the North China Plain. Agric Water Manag 61:219–228

Mark WS, Gregory KE (1998) Effects of mulches on soil properties and tomato production I. soil temperature, soil moisture and marketable yield. Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA, pp. 55–81

Marmiroli N, Lorenzoni C, Michele SA, Terzi V (1989) Preliminary study of the inheritance of temperature stress proteins in barley (Hordeum vulgare L.). Plant Sci 62:147–156

MAF: Ministry of Agriculture and Fisheries (2007) Agricultural and fisheries research report. Ministry of Agriculture and Fisheries, Muscat

Niknam V, Razavi N, Ebrahimzadeh H, Sharifizadeh B (2006) Effect of NaCl on biomass, protein and proline contents, and antioxidant enzymes in seedling and callus of two Trigonella species. Biol Plant 50:591–596

Pessarakli M (1999) Handbook of plant and crop stress. CRC Press, Boca Raton, FL

Petersen FH (1996) Water testing and interpretation. In: Reed DW (ed) Water, media, and nutrition for greenhouse crops. Batavia, Ball, pp 31–49

Ramakrishna A, Hoang MT, Suhas PW, Tranh DL (2006) Effect of mulch on soil temperature, moisture, weed infestation and yield of groundnut in northern Vietnam. Field Crop Res 95:115–125

Richards GA, Pereira LS, Raes D, Smith M (1998) Crop evapo-transpiration: guidelines for computer crop water requirements. FAO Irrigation and Drainage Paper 65, p 5

Saarikko RA, Carter TR (1996) Phenological development in spring cereals: response to temperature and photoperiod under northern condition. Eur J Agron 5:59–70

Serrano R, Mulet J, Rios G, Marquez J, de Larrinoa I, Leube M, Mendizabal I, Pascual-Ahuir A, Proft M, Ros R, Montesinos C (1999) A glimpse of the mechanism of ion homeostasis during salt stress. J Exp Bot 50:1023–1036

Sharma SK, Sing G, Rao GG, Yaduvanshi NPS (2008) Biomass and biodiesel for energy production from salt-affected lands, study findings, India

Sharratt B (1999) Thermal requirements for barley maturation and leaf development in interior Alaska. Field Crop Res 63:179–184

Singh L, Bargali SS, Swamy SL (2006) Production practices and post-harvest management. In: Proceedings of the biodiesel conference toward energy independance – Focus of Jatropha, Hyderabad, India, June 9–10, pp 252–267

Sule A, Vanrobaeys F, Hajos G, Van Beeunen J, Devreese B (2004) Proteomic analysis of small heat shock protein isoforms in barley shoots. Phytochemistry 65:1853–1863

Tewari DN (2007) Jatropha and biodiesel. Ocean Books Ltd., New Delhi

Wani SP, Sreedevi TK (2007) Strategy for rehabilitation of degraded lands and improved livelihoods through biodiesel plantations. In: Proceedings of the 4th international biofuels conference, New Delhi, India, Feb 1–2, pp 50–64

Ward FA, Manuel P (2008) Water conservation in irrigation can increase water use. Proc Natl Acad Sci U S A 105:18215–18220

Yeo AR (1983) Salinity resistance: physiologies and prices. Plant Physiol 58:214–222

Yeo AR (1999) Prediction the interaction between the effects of salinity and climate change on crop plants. Sci Hortic 78:159–174

Zhu JK (2001) Plant salt tolerance. Trends Plant Sci 6:66–71

Zhu JK, Hasegawa PM, Bressan RA (1997) Molecular aspects of osmotic stress in plants. Crit Rev Plant Sci 16:253–277

Chapter 14
Crop Potential of Six *Salicornia bigelovii* Populations Under Two Salinity Water Treatments Cultivated in a Desert Environment: A Field Study

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Abstract Halophyte farming seems to be a promising alternative to conventional agriculture under marginal environments, since it does not compete with dwindling fresh water and land resources. For this purpose halophytic species need to be domesticated to serve as a "crop" plant. Field evaluation of six *Salicornia bigelovii* Torr. populations (LA, GA, MI, FL2, SP, FL1) was conducted in 2012–2013 in the United Arab Emirates applying two irrigation treatments: brackish groundwater (20 dSm^{-1}) and seawater (55 dSm^{-1}) to examine their growth performance taking into account 24 plant characteristics, biomass, seed yield parameters, and growth stages attributes. The experimental results indicated that *S. bigelovii* populations were highly variable for the majority of traits. Irrigation with seawater negatively influenced the agronomic performance of *S. bigelovii* populations compared to groundwater. SP, MI, and GA populations received higher values for almost all characteristics observed, as compared to LA, FL1, and FL2 populations especially under groundwater treatment. Seawater extended the duration of growth cycle for all *Salicornia* populations compared to groundwater irrigation. The outcomes clearly indicated that the salinity level had an impact on *S. bigelovii* populations' performance and yield potential. It is suggested that screening should be evaluated under both optimum and full-strength saline water to optimize biomass and seed production. The existing genotypes could be further improved through breeding taking into account spike characteristics and days to flowering as revealed by path analysis. Combining suitable germplasm with proper agronomic practices, there is a big

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potential to develop this halophytic species plantations for economically viable production systems in hot and dry regions.

Keywords Halophytes · *Salicornia bigelovii* · Crop potential · Seawater farming · Multivariate analyses

14.1 Introduction

With growing demand for food and energy production, new resources are sought to meet population needs. The exploration of marginal environments to increase the agricultural production has raised the interest of scientists and other stakeholders. Marginal areas are mainly located in semiarid and arid climatic zones, where degraded soils and low water quality cannot support agriculture production. Due to the aforementioned limiting factors, the feasibility of seawater agriculture is explored in desert environments (Glenn et al. 1998, 2013). The use of crops that can withstand high saline conditions is extremely important in such a context, especially for marginal lands where no other crops can grow, conserving good quality water for human consumption in parallel.

Developing salt-tolerant crops constitutes a very important strategy to improve yield on salt-affected lands. However, improving salt tolerance in traditional crops through breeding is a laborious process at both plant and cellular level, because of the complexity and multigenic nature of this trait (Ashraf et al. 2008; Cassaniti et al. 2013; Fageria et al. 2012; Flowers 2004). Halophytes flourish in highly saline environments, where conventional crops cannot grow (Shabala 2013). Halophyte cultivation seems to be a promising solution, since these plants already possess the trait of salt tolerance (Rozema and Flowers 2008). Nonetheless, wild halophytic populations need to be collected and bred, so that they can be transformed into productive and profitable crops (Brown et al. 2014a; Ruan et al. 2010).

Salicornia bigelovii Torr. (dwarf glasswort), among other candidate monocots and dicotyledonous halophytic species, has received more attention because of its multifold uses and high salt tolerance (Zerai et al. 2010; Lu et al. 2010; Jaradat and Shahid 2012; Shahid et al. 2013; Glenn et al. 2013; Ventura et al. 2011a, b; Ventura and Sagi 2013; Brown et al. 2014a). *S. bigelovii* belongs to Chenopodiaceae, a popular family for its members tolerant-to-salinity. It is a C3 plant and an annual, succulent euhalophytic species that grows very fast. *S. bigelovii* is a cross-pollinating plant that can also self-pollinate to a lower extent. The fresh tips can be used as salad or pickled directed for human consumption. The biomass can be mixed with other forages and used as livestock feed (Khan and Ansari 2008; Masters et al. 2007). *S. bigelovii* seeds have good qualitative and quantitative oil characteristics ($\approx$30%) and low salt content ($<$3%), attributes that strengthen its importance as oilseed crop with high potential for biofuel production (Brown et al. 2014b; Cybulska et al. 2014a, b; Glenn et al. 1998). The seedcake has high protein content ($\approx$45%) and could be also used as animal feed (Glenn et al. 1991). *S. bigelovii* as a halophytic species of good commercial value has been proposed as a component to be incorporated in farming systems that integrate crops and fish, since the aquaculture effluents constitute a valuable source of nutrients and water for irrigation that could be recycled efficiently (Hamed et al. 2014; Bailis and Yu 2012; Hodges 2004; Brown et al. 1999).

In order to acquire highly productive cultivars with good commercial potential, wild germplasm needs to be domesticated, and selective breeding programs must be undertaken. Zerai et al. (2010), after comparing *S. bigelovii* lines produced in two breeding programs with wild germplasm in greenhouse trials irrigated with brackish water (16 dS^{-1}), concluded that sufficient genetic diversity existed among wild accessions and cultivars to support a crop improvement program using wild *S. bigelovii* populations. Several *S. bigelovii* breeding populations and lines respectively were evaluated for 12 plant traits under high salinity irrigation in field nurseries (Shahid et al. 2013; Jaradat and Shahid 2012).

Literature does not show evaluation studies of *S. bigelovii* germplasm that have been conducted (a) under field conditions in hot and dry climates using different salinity treatments and (b) on a large scale of traits. In the current study, we examined the differentiation in the growth performance of six *S. bigelovii* wild collected populations under two salinity treatments, taking into account a wide variety of agronomic parameters. Secondly, we highlighted those characteristics that are linked with high biomass and seed production under local conditions. Finally, we tested the hypothesis whether the two salinity levels should be used as selection criteria for classification of *S. bigelovii* germplasm which is vital for decision-making on the suitable breeding processes further adopted.

14.2 Materials and Methods

The field experiments were conducted at the facilities of International Center for Biosaline Agriculture (ICBA) (25°05′45.98″ N; 55°23′25.29 E; elevation 30 m) in Dubai, United Arab Emirates. The annual average minimum and maximum temperature were 20.9 °C and 34.8 °C, respectively. The annual mean rainfall was 38.6 mm with average daily evapotranspiration of 5.3 mm. The soil at ICBA experimental station is sandy in texture (sand 98%, silt 1%, and clay 1%). The soil salinity was 768 ppm, and the organic matter content was less than 0.5 (Shahid et al. 2009).

14.2.1 Plant Material and Field Trials

Plant material (seeds) of six wild collections of *S. bigelovii* populations FL1, FL2, GA, MI, LA, and SP were kindly provided by Masdar Institute of Science and Technology (MI) research team.

Table 14.1 Soil salinity (EC_e) and pH for different irrigation water salinity treatments. The values are averages of three replications

		June		August	
		Soil depth (0–25 cm)		Soil depth (0–25 cm)	
S. bigelovii populations	Salinity treatment	EC_e (dS m^{-1})	pH	EC_e (dS m^{-1})	pH
LA	GW	18.3	7.6	19.2	7.7
	SW	31.8	8.0	31.9	7.9
MI	GW	20.5	7.6	20.1	7.6
	SW	35.2	8.1	36.3	7.9
FL2	GW	14.6	7.5	8.6	7.8
	SW	28.9	7.9	44.0	7.9
SP	GW	25.1	7.6	16.4	7.7
	SW	41.2	8.1	36.4	7.9
FL1	GW	17.0	7.6	12.9	7.7
	SW	52.3	8.0	30.5	7.8
GA	GW	19.7	7.5	10.4	7.8
	SW	36.5	8.0	38.2	8.0

GW brackish groundwater, salinity ≈ 20 dS m^{-1}
SW seawater, salinity ≈ 55 dS m^{-1}

Field was prepared adding organic compost at 40 t/ha. The sowing date for *S. bigelovii* seeds was 25th of November 2012. The sowing density was 3 g/m^2, and *S. bigelovii* seeds were lightly covered with soil. Agryl sheets were placed on top of the seeded plots in order to avoid seed losses (by wind and birds) and provide suitable microenvironment for germination. Seeds/seedlings were irrigated with brackish groundwater (GW) (20 dS m^{-1}) and seawater (SW) (55 dS m^{-1}). Plot size was $2 \times 2 = 4$ m^2, and the planting distance was 25×25 cm. The seedlings/plants were irrigated through drip irrigation system with the aforementioned salinity treatments adjusted to the water requirement plus 30% leaching to maintain root zone salinity to a desired level. The total water quantity used for irrigation was 468 m^3 and was applied from sowing until harvest.

The randomized complete block design was followed with three replications for each treatment. The salinity level of GW and SW irrigation was regularly monitored. Soil salinity was checked by taking composite soil sample from various experimental plots representing different treatments from 0 to 25 cm which corresponded to the vital root zone. Soil samples were dried, and soil extract was obtained to determine the electrical conductivity. At the end of the trial, soil samples were again collected and analyzed for salinity and pH. The levels of salinity were maintained throughout the cultivating season with very small fluctuations (Table 14.1). In particular, pH and EC values ranged from 7.5 to 7.8 and from 8.6 to 25.1 dS/m for GW treatment and from 7.8 to 8.1 and from 28.9 to 52.3 dS/m for SW, respectively, for both samplings.

14.2.2 Data Collection

When *S. bigelovii* plants reached the optimum vegetative stage (stage before heading), two lines from each plot were harvested (surface area = 1 m^2), and fresh (green) shoot weight/m^2 was estimated. At final harvest, measurements were taken from 10 plants per experimental plot, and 17 morphological characteristics were recorded. All the characters studied with their abbreviations and units are presented in Table 14.2. SWTPL was calculated as the average of the ten tagged plant values. SWTSQ was measured for each treatment plot (total area = 4 m^2 − 1 m^2 corresponded to green biomass harvest = 3 m^2). HI was estimated as the ratio of seed yield to total above ground crop dry weight. Additionally, *S. bigelovii* plants were monitored for six developmental stages throughout the whole cultivating season. DTOFL were calculated when 5% of the plants were at the anthesis stage. DUFL was the period from when flowering started until all plants bloomed. DTOSP were the total number of days immediately after the end of flowering. DUSP was the period between completion of anthesis and onset of seed maturity. *S. bigelovii* plants mature gradually. DUM initiated when 10% of the plants were mature (light brown

Table 14.2 List of abbreviations for the traits that were studied for *S. bigelovii* plants

	Parameter	Abbreviation	Unit
1	PH	Plant height	cm
2	FIRSTSPKD	Distance between plant base and first developed spike	cm
3	BR	Branches	Number
4	SPK	Spikes	Number
5	RL	Root length	cm
6	SPL	Spike length	mm
7	SPW	Spike width	mm
8	SPWT	Spike weight	g
9	SSSP	Number of seeds/spike	Number
10	SWTSP	Seed weight/spike	g
11	FRSHWT	Fresh shoot weight/m^2	kg/m^2
12	DSHWT	Dry shoot weight/plant	g
13	DRWT	Root dry weight	g
14	ASH	Ash shoot weight/plant	g
15	SSG	Number of seeds/g	Number
16	SWTPL	Seed weight per plant	g
17	SWTSQ	Seed weight/m^2	g/m^2
18	HI	Harvest index	%
19	DTOFL	Days to flowering	Days
20	DUFL	Duration of flowering	Days
21	DTOSP	Days to seed production	Days
22	DUSP	Duration of seed production	Days
23	DUM	Duration of seed maturity	Days
24	GC	Growth cycle	Days

color) and was completed when the plants were totally mature (dark brown color). GC refers to the whole cultivating period of *S. bigelovii* plants.

14.2.3 Data Analysis

Data collected during the growing season were tested for homogeneity of variances before conducting univariate or multivariate statistical analysis. Descriptive statistics (mean and standard error) were estimated for all the data measured. Analysis of variance (ANOVA) was applied to evaluate the variability for the abovementioned growth attributes among *S. bigelovii* populations and between salinity treatments. Least significant difference (LSD) post hoc tests were implemented to detect differences among the average values. Hierarchical cluster analysis was performed in order to identify the relationships among the growth traits in *S. bigelovii* populations grouping in two different salinities. Ward's method was used to classify the data. Correlation analysis was also computed using Pearson's test. Pathway analysis was conducted, in order to examine the direct and indirect associations of various growth characteristics on SWTSQ. Path analysis differs from simple correlations in the sense that it points out the causes and their relative importance, whereas the latter simply measures the mutual association ignoring the causation. All statistical analyses were performed with JMP statistical software version 8.0 (SAS Institute, Inc., Cary, NC, USA).

14.3 Results

14.3.1 Impact of Salinity Treatments on Growth Parameters of S. bigelovii *Populations*

Generally, plant characteristics differentiated to a greater extent when irrigated with GW compared to SW for all *S. bigelovii* populations (Table 14.3). SPK and BR were the characteristics most negatively affected by SW compared to GW treatment for all halophytic genotypes, and the differences ranged from −95% to −629% and from −52% to −124%, respectively. PH was also reduced after SW in contrast with GW application for all populations; however, the differences that varied between −3% and −105% were not all statistically significant. FIRSTSPKD, SPL, SPWT, and RL were either positively, negatively, or neutrally influenced by the higher salinity treatment among *S. bigelovii* populations. In contrast, an increase in SPW was observed for most *S. bigelovii* populations irrigated with SW except from SP and GA genotypes, which they did not demonstrate statistically significant differences between salinity treatments for the specific characteristic. Under GW irrigation, MI, SP, and GA plants were characterized as taller (59.8, 60.6, and 50.9 cm,

Table 14.3 Plant characteristics of six *S. bigelovii* populations irrigated with brackish groundwater (GW) and seawater (SW). Values (mean ± s.e.) followed by dissimilar letter imply statistically significant difference ($p \leq 0.01$ and $p < 0.05$)

		Salicornia bigelovii populations											
Plant characteristics	Salinity treatments	LA	Difference (a−b)/a*100%	MI	Difference (a−b)/a*100%	FL2	Difference (a−b)/a*100%	SP	Difference (a−b)/a*100%	FL1	Difference (a−b)/a*100%	GA	Difference (a−b)/a*100%
PH (cm)	GW (b)	37.1 ± 1.6 bc		59.8 ± 5.2 g		41.0 ± 2.1 cd		60.6 ± 4.0 g		46.3 ± 4.9 ef		50.9 ± 0.5 f	
	SW (a)	36.0 ± 1.7 b	−3	45.4 ± 0.9 de	−32	36.7 ± 4.6 bc	−12	45.9 ± 2.6 def	−32	45.1 ± 2.2 de	−3	24.8 ± 2.8 a	−105
FIRSTSPKD (cm)	GW (b)	7.5 ± 0.8 a		11.2 ± 0.9 abc		10.4 ± 0.8 abc		13.0 ± 1.1 cd		9.8 ± 1.6 ab		10.9 ± 0.3 abc	
	SW (a)	11.5 ± 1.1 bc	35	10.7 ± 0.7 abc	−5	9.5 ± 0.9 ab	−9	10.8 ± 0.5 bc	−20	15.0 ± 1.6 d	35	9.3 ± 2.2 ab	−17
BR	GW (b)	33.5 ± 0.2 cd		36.9 ± 1.6 cd		31.9 ± 3.3 c		37.0 ± 2.5 cd		33.1 ± 2.8 c		38.8 ± 0.1 d	
	SW (a)	20.8 ± 0.8 ab	−61	21.8 ± 0.6 ab	−69	19.7 ± 2.8 b	−62	20.6 ± 2.0 ab	−80	21.8 ± 1.9 ab	−52	17.3 ± 3.4 a	−124
SPK	GW (b)	156.5 ± 95.5 d		311.5 ± 43.1 e		311.1 ± 52.5 e		333.8 ± 47.6 ef		222.2 ± 47.9 d		373.0 ± 31.5 f	
	SW (a)	72.3 ± 2.7 ab	−116	64.8 ± 5.2 ab	−381	148.0 ± 16.8 c	−110	45.8 ± 3.9 a	−629	114.0 ± 5.8 bc	−95	92.2 ± 10.6 abc	−305
SPL (mm)	GW (b)	50.2 ± 6.3 abc		109.4 ± 7.4 e		48.0 ± 3.1 a		115.0 ± 5.5 e		62.8 ± 4.3 c		85.3 ± 2.3 d	
	SW (a)	60.6 ± 2.2 bc	17	82.4 ± 4.0 d	−33	52.1 ± 4.6 ab	8	116.5 ± 13.2 e	1	52.1 ± 1.4 ab	−21	54.3 ± 2.5 abc	−57
SPW (mm)	GW (b)	3.1 ± 0.2 a		3.7 ± 0.1 def		3.1 ± 0.2 ab		4.1 ± 0.3 g		3.2 ± 0.1 ab		3.2 ± 0.1 ab	
	SW (a)	3.4 ± 0.1 bcd	9	4.2 ± 0.3 g	12	3.6 ± 0.2 cde	14	4.1 ± 0.1 fg	0	3.9 ± 0.3 efg	18	3.3 ± 0.5 abc	3
SPWT (mg)	GW (b)	134 ± 20 ab		495 ± 40 e		142 ± 21 a		533 ± 23 e		205 ± 18 abc		254 ± 13 c	
	SW (a)	206 ± 12 abc	35	391 ± 22 d	−27	208 ± 31 abc	32	540 ± 43 e	1	233 ± 13 c	12	167 ± 16 bc	−52
RL (cm)	GW (b)	13.7 ± 2.1 bc		18.6 ± 0.5 cd		13.8 ± 1.8 ab		19.6 ± 0.9 d		11.6 ± 1.2 a		17.9 ± 1.1 d	
	SW (a)	13.7 ± 0.6 ab	0	12.4 ± 1.6 ab	−50	12.2 ± 0.7 ab	−13	11.4 ± 1.7 a	−72	12.3 ± 0.5 ab	6	13.3 ± 1.0 ab	−35

The abbreviations are explained in detail in Table 14.2

respectively), having the highest number of BR (36.9, 37.0 and 38.8) and SPK (311.5, 333.8 and 373.0), increased RL (18.6, 19.6 and 17.9 cm), the FIRSTSPKD was developed in a higher level (11.2, 13.0 and 10.9 cm), and their spikes were longer (109.4, 115.0 and 85.3 mm) and heavier (495, 533 and 254 mg) compared to LA, FL1, and FL2 plants. The former group of *S. bigelovii* populations maintained their preponderance for most of the characteristics even after SW application.

DSHWT, DRWT, and ASH measurements were significantly reduced for all *S. bigelovii* genotypes after SW compared to GW irrigation, and the differences ranged from −30% to −498%, 31% to −532%, and − 9% to −35%, respectively (Table 14.4). FRSHWT decreased dramatically for MI (−476%), SP (−407%), and GA (−618%) plants and to a lower extent for FL2 (−78%) and LA (−8%) populations after high salinity treatment. In contrast, green biomass slightly increased for FL1 (6%). Both SWTPL and SWTSQ were severely affected by SW treatment for MI (−191% and −250%, respectively), SP (−133% and −388%), and GA (−165% and −201%) genotypes. In contrast, high salinity provoked an increase in SWTSQ for LA (38%), FL1 (52%), and FL2 (21%) genotypes, although it was not statistically significant. Indifferent results were obtained for LA and FL1 populations for SWTPL between the two treatments; however, a slight decrease was observed for FL2 (−9%). The SSG is related to the size of the seed; hence the higher the number, the smaller the size of the seeds. Generally, more, but smaller and lighter seeds were produced after GW compared to SW treatments for all populations, except for MI which SSG remained almost similar in both irrigation treatments. A number of seeds per spike of MI and GA plants were significantly decreased after SW irrigation. For the rest of *S. bigelovii* populations, no statistical significant differences were spotted between the treatments, although an increase was observed in genotypes LA and FL2 for this spike parameter. None statistical significant difference was observed for SWTSP for all *S. bigelovii* genotypes, although a considerable decrease was observed for MI and GA populations under high salinity treatment.

Finally, HI increased because of higher salinity impact for all *S. bigelovii* genotypes, and the increase varied between 13% and 59%. However, HI values were statistically significant only for MI, SP, and GA populations. High HI values do not necessarily reflect higher seed yield but significantly less biomass due to high salinity levels, which finally increased the ratio [seed weight/(seed weight + biomass)]. Overall, MI and SP populations excelled for almost all seed and biomass yield measurements in both salinity treatments. GA also received comparable satisfying values for most yield characteristics under GW treatment; however, it did not maintain its good performance at higher salinity level. FL1 and FL2 populations irrigated with SW outperformed for several yield parameters such as FRSHWT (3.5 and 3.2 kg/m^2) even surpassing MI and SP at the same treatment.

Early flowering was observed for MI, SP, and GA populations and ranged from 134.7 (MI) to 142.3 (SP) and from 124.7 (MI) to 151.0 (SP) days for GW and SW treatments, respectively, whereas LA, FL1, and FL2 populations exhibited late flowering after several weeks in both applications (Table 14.5). SW irrigation extended DUFL for all *S. bigelovii* genotypes from 12% to 25%, except from LA (−30%). After anthesis stage, SW compared to GW extended the duration of growth

Table 14.4 Seed yield, biomass, ash, and root parameters of six *S. bigelovii* populations treated with brackish groundwater (GW) and seawater (SW). Values (mean ± s.e.) followed by dissimilar letter imply statistically significant difference ($p \leq 0.01$ and $p < 0.05$)

			Salicornia bigelovii populations										
Seed and biomass yield measurements	Salinity treatments	LA	Difference (a−b)/ a*100%	MI	Difference (a−b)/ a*100%	FL2	Difference (a−b)/ a*100%	SP	Difference (a−b)/ a*100%	FL1	Difference (a−b)/ a*100%	GA	Difference (a−b)/ a*100%
FRSHWT (kg/m^2)	GW	2.7 ± 1.0 a		14.4 ± 0.6c		5.7 ± 0.9 b		14.2 ± 1.3 c		3.3 ± 0.9 a		12.2 ± 1.6 c	
	SW	2.5 ± 0.1 a	−8	2.5 ± 0.5 a	−476	3.2 ± 0.4 a	−78	2.8 ± 0.1 a	−407	3.5 ± 0.5 ab	6	1.7 ± 0.0 a	−618
DSHWT (g)	GW	132.4 ± 25.3 de		205.9 ± 19.1 f		104.9 ± 8.7 cde		212.4 ± 43.1 f		88.1 ± 18.2 bcd		151.3 ± 6.3 e	
	SW	42.7 ± 4.4 ab	−210	49.5 ± 4.5 ab	−316	67.4 ± 21.7 abc	−56	44.2 ± 8.7 ab	−381	67.6 ± 8.1 abc	−30	25.3 ± 5.7 a	−498
DRWT (g)	GW	10.5 ± 2.5 de		12.5 ± 0.4 e		9.3 ± 0.7 cd		12.0 ± 0.7 de		6.4 ± 1.5 bc		12.7 ± 0.5 e	
	SW	3.7 ± 0.4 ab	−184	2.1 ± 0.4 a	−495	4.1 ± 1.1 ab	−127	1.9 ± 0.7 a	−532	4.9 ± 1.0 ab	−31	2.5 ± 1.0 a	−408
ASH (g)	GW	0.26 ± 0.04 abc		0.35 ± 0.04 abc		0.30 ± 0.01 cd		0.27 ± 0.01 abc		0.29 ± 0.01 bcd		0.24 ± 0.02 ab	
	SW	0.23 ± 0.01 a	−13	0.26 ± 0.01 d	−35	0.24 ± 0.01 ab	−25	0.23 ± 0.01 ab	−17	0.22 ± 0.01 a	−32	0.22 ± 0.03 a	−9
SSG	GW	7094.7 ± 321.3 e		3136.3 ± 82.3 ab		4069.7 ± 89.0 bcd		3766.7 ± 172.1 bcd		4800.7 ± 921.3 d		4568.7 ± 466.3 cd	
	SW	3806.3 ± 456.3 bcd	−86	3209.3 ± 219.2 ab	2	2029.7 ± 141.2 a	−101	3499.7 ± 361.5 bc	−8	3371.3 ± 603.5 bc	−42	3764.7 ± 369.3 bcd	−21
SSSP	GW (b)	32.8 ± 8.0 ab		147.8 ± 6.0 e		20.1 ± 5.3 a		135.6 ± 20.9 de		24.7 ± 4.6 ab		127.7 ± 3.8 de	
	SW (a)	48.7 ± 3.1 bc	33	114.9 ± 4.4 d	−29	24.6 ± 5.1 ab	18	134.5 ± 9.8 de	−1	24.6 ± 2.9 ab	−0.4	68.4 ± 19.8 c	−87
SWTSP (mg)	GW (b)	4.3 ± 1.6 a		47.2 ± 2.7 e		4.5 ± 2.1 a		37.4 ± 6.4 de		5.8 ± 1.7 a		28.6 ± 3.6 cd	
	SW (a)	13.4 ± 2.5 ab	68	36.2 ± 3.0 de	−30	10.1 ± 5.2 ab	55	38.9 ± 5.5 de	4	7.7 ± 1.3 ab	25	19.2 ± 6.9 bc	−49
SWTPL (g)	GW	1.2 ± 0.6 a		6.4 ± 0.3 c		2.3 ± 0.3 a		4.9 ± 0.8 b		1.7 ± 0.2 a		4.5 ± 0.4 b	
	SW	1.2 ± 0.1 a	0	2.2 ± 0.3 a	−191	2.1 ± 0.4 a	−9	2.1 ± 0.5 a	−133	1.7 ± 0.4 a	0	1.7 ± 0.4 a	−165
SWTSQ (g/m^2)	GW	7.3 ± 1.6 a		127.1 ± 6.8 e		13.7 ± 2.9 ab		85.4 ± 3.6 d		9.6 ± 1.3 a		82.0 ± 6.3 d	
	SW	11.8 ± 2.3 ab	38	36.3 ± 2.1 c	−250	17.3 ± 2.3 ab	21	17.5 ± 7.6 ab	−388	19.8 ± 11.5 ab	52	27.2 ± 7.8 bc	−201
HI (%)	GW	1.1 ± 0.7 a		3.1 ± 0.4 cd		2.1 ± 0.2 ab		2.3 ± 0.1 ab		2.1 ± 0.6 ab		2.9 ± 0.2 bc	
	SW	2.7 ± 0.1 b	59	4.3 ± 0.2 bcd	28	3.3 ± 0.7 bcd	36	4.5 ± 0.2 d	49	2.4 ± 0.4 ab	13	6.4 ± 1.0 e	55

The abbreviations are explained in detail in Table 14.2

Table 14.5 Stages of the growth cycle of six *S. bigelovii* populations irrigated with brackish groundwater (GW) and seawater (SW). Values (mean ± s.e.) followed by dissimilar letter imply statistically significant difference ($p \leq 0.01$ and $p < 0.05$)

			Salicornia bigelovii populations										
Growth stages	Salinity treatments	LA	Difference a−b)/ a*100%	MI	Difference (a−b)/ a*100%	FL2	Difference (a−b)/ a*100%	SP	Difference (a−b)/ a*100%	FL1	Difference (a−b)/ a*100%	GA	Difference (a−b)/ a*100%
DTOFL	GW	179.7 ± 5.7 cd		134.7 ± 10.7 ab		189.7 ± 1.5 d		142.3 ± 11.4 ab		189.0 ± 1.1 cd		136.7 ± 3.5 ab	
	SW	170.7 ± 4.4 c	−5	124.7 ± 1.3 a	−8	182.7 ± 3.7 cd	−4	151.0 ± 4.2 b	6	181.0 ± 4.6 cd	−4	149.0 ± 11.8 b	8
DUFL	GW	56.0 ± 5.5 de		47.7 ± 10.9 cde		24.3 ± 0.9 a		37.7 ± 9.9 abcd		25.7 ± 3.0 ab		40.3 ± 1.5 abcd	
	SW	43.0 ± 4.9 bcde	−30	59.7 ± 12.2 e	20	28.7 ± 3.7 ab	15	50.0 ± 6.4 de	25	29.3 ± 1.2 abc	12	50.3 ± 0.9 de	20
DTOSP	GW	244.0 ± 1.9 a		249.3 ± 1.2 ab		244.7 ± 0.5 a		249.1 ± 1.4 ab		246.2 ± 1.4 a		249.1 ± 0.6 ab	
	SW	266.5 ± 3.8 c	8	255.2 ± 4.4 b	2	264.8 ± 1.3 c	8	267.5 ± 1.4 c	7	266.0 ± 1.8 c	7	266.0 ± 3.0 c	6
DUSP	GW	10.4 ± 0.6 a		66.9 ± 1.5 cde		30.7 ± 1.5 b		69.1 ± 3.7 cde		31.5 ± 2.5 b		72.1 ± 3.2 e	
	SW	52.9 ± 5.3 c	80	70.9 ± 8.0 de	6	53.5 ± 6.8 cd	43	66.5 ± 8.4 cde	−4	55.7 ± 1.7 cde	43	66.7 ± 14.4 cde	−8
DUM	GW	18.8 ± 2.4 a		21.1 ± 2.0 ab		18.5 ± 1.3 a		18.8 ± 0.8 a		21.7 ± 3.6 abc		32.3 ± 0.6 de	
	SW	32.3 ± 2.8 de	42	32.5 ± 1.6 de	35	40.3 ± 7.3 e	54	28.2 ± 2.3 bcd	33	30.5 ± 5.0 cd	29	32.3 ± 2.2 de	0
GC	GW	264.1 ± 1.3 a		270.4 ± 1.8 a		263.2 ± 1.8 a		267.9 ± 1.5 a		267.9 ± 2.7 a		281.4 ± 0.7 b	
	SW	298.8 ± 2.1 d	12	287.7 ± 6.0 bc	6	305.1 ± 7.4 d	14	295.7 ± 3.4 cd	9	296.5 ± 3.3 cd	10	298.4 ± 5.2 cd	6

The abbreviations are explained in detail in Table 14.2

stages of *S. bigelovii* plants. Ten to twenty two more days were needed for all *S. bigelovii* genotypes to reach seed production stage. DUSP was also prolonged from 4 to 42 days for LA, MI, FL1, and FL2, whereas the opposite, although not significant effect, was observed for SP and GA populations at higher salinity application. DUM was also significantly extended after SW treatment for all *S. bigelovii* populations, apart from GA which salinity effect was neutralized. Finally, *S. bigelovii* plants completed their GC 17 to 42 days later after irrigation with SW compared to GW. MI was characterized by the shortest GC at high salinity rate (287.7 days).

14.3.2 Grouping of S. bigelovii *Populations Based on GW and SW Treatments*

Hierarchical clustering revealed three main clusters based on plant growth (A, B, C) (Fig. 14.1). MI, SP, and GA populations excelled for the majority of the plant attributes under GW irrigation and were grouped in Cluster A. Cluster B contained all *S. bigelovii* populations treated with SW and was divided into two sub-clusters (D and E). Cluster D encompassed LA, FL1, FL2, and GA, and this cluster was placed next to cluster C, where the same populations congregated after irrigation with GW. MI and SP populations treated with SW assembled in Cluster E. Cluster analysis showed that the halophytic populations were separated to the two salinity treatments based on their overall response.

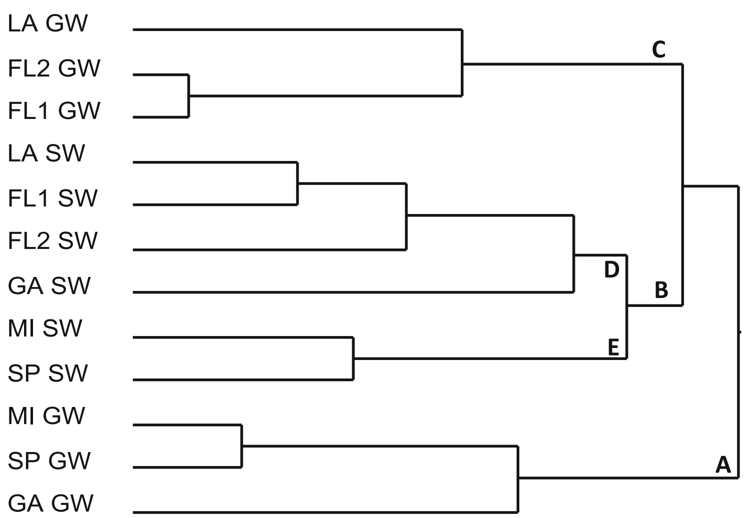

Fig. 14.1 Clustering for six *S. bigelovii* populations (LA, GA, MI, FL2, SP, FL1) irrigated with brackish groundwater (GW) and seawater (SW) for all parameters studied

14.3.3 Correlations and Interrelationships Among the Characters Studied Comparing the Two Salinities Treatments

Out of 276 possible pairwise correlation coefficients for all 24 plant growth parameters, 176 (64%) were significant for GW and only 57 (21%) for SW treatment (Table 14.6). 94% and 88% of significant correlations for GW and SW treatment, respectively, were higher than 0.500 implying the strong association (negative or positive) among the traits. Positive associations were noted between SWTSQ and the rest of the traits except for SSG (−0.590) and DTOFL (−0.865) for *S. bigelovii* plants irrigated with GW. Negative correlation between SWTSQ and DTOFL (−0.524) was also observed for SW treatment. The same associations were observed between FRSHWT and other growth parameters for GW application. However, FRSHWT was negatively correlated only with harvest index for *S. bigelovii* populations treated with SW. ASH was not correlated with any other character for both treatments.

Pathway analysis was used to partition the observed correlation coefficient into direct and indirect effects of several components on SWTSQ, in order to provide clear picture of the interrelationships among traits. Subramanian and Subramanian (1994) determined the values for direct and indirect effects path analysis as follows: value of >1 (very high), 0.3–0.99 (high), 0.2–0.29 (moderate), 0.1–0.19 (low), and <0.1 (negligible).

SWTSP, SSSP, and SPL were characterized by the highest direct effects 0.604, 0.467, and −0.302, respectively, whereas moderate effects were observed for SPK, DUSP, and HI (−0.208, 0.250 and 0.226, respectively) for *S. bigelovii* populations irrigated with GW. On the other hand, SW application significantly increased the values of direct effects for several parameters such as BR (0.302), SSSP (1.537), SWTSP (−1.516), DTOFL (−0.752), and DUM (0.472). Lower direct effects were spotted for the rest of the parameters.

SSSP was characterized by high and positive direct and total effects (correlations) for both water treatments, and this meant that the correlation explained the true relationship and this trait should be considered one of the characters for *S. bigelovii* improvement in a breeding program. The same observation was made for SWTSP only for GW application. In contrast, for SW treatment, a very high and negative direct effect was noted, but a positive and moderate correlation was observed. When a high positive or negative correlation is observed, but the direct effects are negative and positive respectively or negligible, then the indirect effects are the cause of correlation. Such findings were observed for BR, SPK, SPL, DTOFL, DUM, and HI for *S. bigelovii* populations irrigated with GW and for SWTSP, DUSP, and HI for *S. bigelovii* populations irrigated with SW. SSSP and SWTSP were the parameters with the highest indirect effect in all cases followed by DTOFL and SPL. SPK and SPL were characterized by low and negligible direct and correlation effects in SW treatment.

Table 14.6 Pearson correlation analysis conducted for all growth attributes for the six *S. bigelovii* populations. Only the statistically significant coefficients are presented ($p < 0.01$ and $p < 0.05$). Values above diagonal (gray color) refer to seawater (SW) and below diagonal to brackish groundwater (GW) treatment

	PH	FIRSTSPKD	BR	SPK	RL	SPL	SPW	SPWT	SSSP	SWTSP	FRSHWT	DSHWT	DRWT	ASH	SSG	SWTPL	SWTSQ	HI	DTOFL	DUFL	DTOSP	DUSP	DUM	GC
PH	1						0.773**	0.640**			0.653**	0.623**						−0.501*						
FIRSTSPKD	0.773**	1									0.582*		0.726**											
BR	0.710**	0.511*	1																					
SPK	0.525*	0.598**	0.493*	1		−0.674**		−0.591**	−0.728**	−0.590**		0.555*	0.597**		−0.516*				0.538*	−0.590**				
RL	0.706**	0.577*	0.533*	0.649**	1																			
SPL	0.916**	0.682**	0.547*	0.476*	0.795**	1		0.960**	0.825**	0.746**										0.534*				
SPW	0.766**	0.513*			0.545*	0.766**	1	0.545*	0.478*	0.577*	0.506*	0.527*				0.748**	0.475*		−0.473*			0.626**		
SPWT	0.901**	0.667**			0.728**	0.969**	0.829**	1	0.819**	0.792**									−0.474*					
SSSP	0.819**	0.558*	0.602**	0.554*	0.852**	0.924**	0.666**	0.846**	1	0.959**			-0.671**						−0.821**	0.687**		0.546*		
SWTSP	0.872**	0.595**	0.571*	0.508*	0.824**	0.942**	0.721**	0.904**	0.968**	1			-0.581*						−0.829**	0.608**		0.633**		
FRSHWT	0.824**	0.655**	0.624**	0.590*	0.839**	0.888**	0.649**	0.837**	0.909**	0.912**	1	0.792**	0.617**					−0.551*						
DSHWT	0.896**	0.825**	0.659**	0.503*	0.781**	0.869**	0.688**	0.853**	0.803**	0.854**	0.870**	1	0.639**			0.552*		−0.586*		−0.495*				
DRWT	0.493*		0.485*		0.718**	0.560*		0.473*	0.664**	0.611**	0.622**	0.623**	1						0.558*					
ASH														1										
SSG	−0.730**	−0.779**		−0.603**	−0.532*	−0.612**	−0.492*	−0.636**	−0.541*	−0.646**	−0.680**	−0.680**			1									
SWTPL	0.795**	0.615**	0.597**	0.567*	0.789**	0.846**	0.554*	0.800**	0.882**	0.905**	0.921**	0.893**	0.603**		−0.636**	1	0.512*							
SWTSQ	0.772**	0.523*	0.557*	0.470*	0.771**	0.871**	0.570*	0.831**	0.938**	0.940**	0.911**	0.808**	0.609**		−0.590**	0.950**	1		−0.524*					
HI				0.612**	0.487*	0.480*			0.541*	0.519*	0.595**					0.701**	0.632**	1	−0.491*	0.495*				
DTOFL	−0.760**		−0.593**	−0.486*	−0.727**	−0.856**	−0.591**	−0.770**	−0.949**	−0.893**	−0.822**	−0.679**	−0.614**			−0.759**	−0.865**		1	−0.718**		−0.689**		
DUFL																			−0.537*	1				
DTOSP	0. 643**	0.527*			0.600**	0.729**		0.649**	0.710**	0.696**	0.700**	0.784**	0.548*			0.772**	0.735**	0.558*	−0.618**		1			0.616**
DUSP	0.782**	0.678**	0.568*	0.581*	0.713**	0.855**	0.550*	0.767**	0.894**	0.853**	0.902**	0.798**	0.532*		−0.648**	0.864**	0.889**	0.638**	−0.840**		0.802**	1		
DUM				0.478*																			1	0.741**
GC			0.539*		0.499*				0.581*		0.526*					0.505*	0.531*		−0.543*		0.513*	0.657**	0.926**	1

*The value is significant when $p < 0.05$. **The value is significant when $p < 0.01$

14.4 Discussion

14.4.1 *Differentiation of Growth Performance of* S. bigelovii *Populations Comparing GW and SW Treatments*

Screening and evaluation of six *S. bigelovii* populations irrigated with GW and SW, under field conditions, revealed large differences among themselves and between the treatments. The high variation in the characteristics measured indicated that these are highly variable populations, presumably due to the outcrossing nature of the breeding system (Zerai et al. 2010; Martinez-Garcia 2010; Jaradat and Shahid 2012). Significant intraspecific variation in salt tolerance has been observed for various halophytic grasses such as *Spartina patens*, *Spartina alterniflora* (Hester et al. 2001), and *Distichlis spicata* (Aschenbach 2006). Under elevated salinities, the study of variation within and between species can give insight into physiological adaptations that result in morphological changes (Hester et al. 2001).

MI, SP, and GA were characterized by higher values for the majority of characteristics, compared to LA, FL1, and FL2 populations for both treatments. They were also characterized by early-flowering habit, a desirable characteristic especially for hot and arid environments as observed in Eritrea region by Zerai et al. (2010). All wild accessions, breeding populations, and lines of *S. bigelovii* differentiated for most of the parameters measured, when irrigated with water which salinity was 17 dS m^{-1} (Zerai et al. 2010) and >40 dS m^{-1} (Jaradat and Shahid 2012). The maximum seed yield was obtained by MI (1.27 t/ha), SP (0.85 t/ha), and GA (0.82 t/ha) populations treated with GW. However, seed production was less than 1.39–2.46 t/ha for *Salicornia* plants irrigated with SW as reported in Glenn et al. (1999). The seed production of LA, FL1, and FL2 populations was slightly higher after SW irrigation, although it remained very low and did not exceed 0.2 t/ha. However, attention should be drawn to the fact that FL1 population produced two times more seed after SW (0.2 t/ha) compared to GW (0.1 t/ha) treatment. The mechanism that is involved to overcome increased salinity levels and produce more seeds could be further investigated. MI, SP, and GA populations also received the maximum values for FRSHWT and DSHWT after irrigation with GW. Green biomass values were the highest ever reported in the literature ranging from 120 to 140 t/ha. It should be mentioned that the values extrapolated from 1 m^2 to a hectare and that the experimental plots were small in size (4 m^2) and well-managed and sufficient water was provided to each plant through drip irrigation system. DSHWT and DRWT were significantly reduced after SW treatment compared to root length values. It has been observed that shoot growth was more sensitive than root growth to elevated salinities (Munns and Tester 2008; Läuchli and Grattan 2007). This is due to the fast root recovery compared to shoots (Munns 2002). Differences in shoot growth could result from increased production of nodes or increased size of internodes, as a result of increased cell division and/or elongation, when plants are grown in optimal salinity (Ayala and O'Leary 1995). SPL (>11 cm) measured for the current populations exceeded the ones observed for *Salicornia* accessions from other studies (Jaradat and Shahid 2012; Shahid et al. 2013). Glenn et al. (1997) reported an average SPL of 3–5 cm as compared to 10–15 cm spike length of native *Salicornia*. The increase in SPW, which was monitored after SW irrigation, constituted a physiological response often observed in plants grown under high saline conditions, which is attributed to Na and Cl accumulation (Karabourniotis et al. 2012).

SW compared to GW extended the duration of the growth stages after flowering and the whole growth cycle as a consequence. A common feature of plant response to salinity is the inhibition of growth and productivity. Slower growth is an adaptive characteristic for plant survival under stress, since it allows plants to rely on multiple resources (e.g., building blocks and energy) to combat the stress (Zhu 2001). According to Ventura et al. (2011b), cultivation based on full-strength seawater (≈48 dS/m) had no effect on the general flowering pattern of the different Salicornieae types.

The assemblage of MI, SP, and GA populations through cluster analysis confirmed their supremacy under GW and SW irrigation and could be characterized as high-yielding populations, compared to LA, FL1, and FL2 which could be denoted as low-yielding populations. Although GA plants were characterized by slower growth compared to MI and SP plants after SW treatment, they still performed better compared to LA, FL1, and FL2 populations.

14.4.2 Traits Targeted for Improving High-Yielding **S. bigelovii** *Populations*

Correlation analyses showed that most of the studied parameters were highly correlated among themselves, implying that salt tolerance is a multigenic trait which is reflected on morphological, physiological, and biochemical aspects (Munns and Tester 2008; Flowers 2004). In addition, yield is a very complex feature resulting from the process of plant growth. For the halophytic species, *S. bigelovii* positive and significant associations were observed between yield (seed or biomass) and some other traits especially for GW irrigation. This observation is favorable for breeding, since selection for one trait may produce correlated response for improvement of other traits, which are positively associated with it (Pandey et al. 2012; Yadav et al. 2013; Subramanian and Subramanian 1994). In particular, spike characteristics maintained their high association among themselves even after SW treatment. Similar results were obtained by Jaradat and Shahid (2012), who observed that, under SW treatment, seed morphometric characteristics were highly correlated (>0.5) among themselves and with seed yield.

Pathway analysis revealed that selection for SPWT and SSSP may lead to improved germplasm for seed yield (Table 14.7). SPWT is highly correlated with SPL which is also correlated with the SSSP it encloses (Shahid et al. 2013). DTOFL was another desirable trait revealed from the current study that should be selected as criterion for further genotypes' improvement, in order to compress the GC so that

Table 14.7 Pathway analysis of selected attributes that impacted seed yield (SWTSQ) for the six *S. bigelovii* populations irrigated with brackish groundwater (GW) and seawater (SW)

Traits	Salinity treatment	Direct effect	Indirect effect 1	2	3	4	5	6	7	8	9	Total indirect effect	Total effect/ correlations
BR (1)	GW	0.099		−0.102	−0.162	0.281	0.345	−0.073	0.142	−0.017	0.044	0.458	0.557
	SW	0.302		−0.005	−0.017	0.206	−0.157	0.053	−0.012	−0.131	0.009	−0.053	0.249
SPK (2)	GW	−0.208	0.049		−0.141	0.258	0.307	−0.059	0.145	−0.020	0.138	0.678	0.470
	SW	0.154	−0.010		0.129	−1.118	0.894	−0.405	0.015	0.216	0.007	−0.271	−0.118
SPL (3)	GW	−0.302	0.054	−0.099		0.425	0.569	−0.105	0.214	−0.006	0.108	1.167	0.871
	SW	−0.191	0.026	−0.104		1.268	−1.131	0.337	−0.013	−0.093	−0.005	0.285	0.094
SSSP (4)	GW	0.467	0.060	−0.115	−0.274		0.585	−0.116	0.224	−0.015	0.122	0.470	0.937
	SW	1.537	0.041	−0.112	−0.157		−1.453	0.617	−0.040	−0.109	−0.011	−1.225	0.311
SWTSP (5)	GW	0.604	0.057	−0.106	−0.279	0.452		−0.109	0.214	−0.009	0.117	0.336	0.940
	SW	−1.516	0.031	−0.091	−0.142	1.473		0.623	−0.047	−0.068	−0.009	1.771	0.255
DTOFL (6)	GW	0.122	−0.059	0.101	0.254	−0.443	−0.540		−0.210	0.014	−0.104	−0.987	−0.865
	SW	−0.752	−0.021	0.083	0.085	−1.262	1.256		0.051	0.020	0.016	0.228	−0.524
DUSP (7)	GW	0.250	0.056	−0.121	−0.253	0.417	0.516	−0.103		−0.018	0.144	0.638	0.889
	SW	−0.074	0.049	−0.032	−0.033	0.839	−0.959	0.518		0.021	−0.008	0.395	0.321
DUM (8)	GW	−0.043	−0.084	0.070	0.038	−0.356	0.218	−0.032	−0.003		0.005	−0.144	0.285
	SW	0.472	0.041	−0.099	−0.045	0.164	0.132	−0.041	0.104		0.072	0.327	0.328
HI (9)	GW	0.226	−0.085	−0.032	−0.029	0.536	−0.426	0.369	−0.018	−0.067		0.247	0.631
	SW	−0.033	0.019	−0.127	−0.142	0.252	0.313	−0.056	0.160	−0.014		0.404	0.214

Total indirect effects constitute the sum of indirect effects per row (direct effects not included). Correlation of characteristic X on seed yield per plant constitutes the sum between the direct effect of characteristic X and the total indirect effects of the rest of the traits through characteristic X
The abbreviations are explained in detail in Table 14.2

summer months could be avoided (Zerai et al. 2010). Although HI was not as high as reported from Zerai et al. (2010) and Glenn et al. (1991), it can also be improved through reproductive traits. Desirable traits that also need to be taken into account in a breeding program would be shorter plants, in order to avoid lodging, with considerable BR and SPK that should be placed in a higher level so that plucking could be facilitated (Zerai et al. 2010). Path analysis implemented for eleven *S. bigelovii* genotypes irrigated with SW (55 dS m^{-1}) validated the findings of the current study since similar spike parameters and growth stages were highlighted for selection to improve seed production (Lyra et al. 2016).

14.4.3 Water Salinity Levels as Selection Criteria for Screening S. bigelovii *Germplasm*

The threshold of the water salinity and suitable selection criteria used to evaluate ecotypes within a species for salinity tolerance are of highly importance for breeding purposes and have been discussed in several studies (Ruan et al. 2010; Lee et al. 2005, 2004a, b; Ashraf 2004; Zeng et al. 2002). Lee et al. (2004a) emphasized that evaluation of seashore paspalum ecotypes, at water salinity <20 dS m^{-1}, was not sufficient for assessing salinity tolerance. Previous studies only focused on one salinity regime assessment for screening *S. bigelovii* lines and accessions. In the current study, *S. bigelovii* plants growth was significantly stimulated by salinity of EC $= 20$ dS m^{-1}, compared to salinity of EC $= 55$ dS m^{-1}. Similar findings were obtained for the same halophytic species (Ayala and O'Leary 1995) and for the perennial halophyte *Suaeda fruticosa* (Khan et al. 2000). Salinity around 20 dS m^{-1} constitutes the optimum concentration for *S. bigelovii* and other halophytes growth (Panta et al. 2014; Katschnig et al. 2013; Flowers and Colmer 2008; Ayala and O'Leary 1995). In addition, the highest salinity level to which *S. bigelovii* would be expected to be exposed for screening ecotypes within a species is needed, in order to examine the highest degree of salinity tolerance (Ruan et al. 2010). Besides, SW is the only available water resource to irrigate *S. bigelovii* or any other halophytic species along coastal deserts, so the plant material that is going to be used must be characterized by high growth rates under such elevated saline conditions (Brown et al. 2014a). As a result, GW and SW used in the present study could be considered as optimum and maximum salinity levels, respectively, for *S. bigelovii* growth. High-yielding populations of MI and SP outperformed under GW irrigation, and they maintained their preponderance even at SW salinity, although population growth was significantly hampered. In addition, high salinity affected GA population to a greater extent, which performance resembled the growth of low-yielding populations. Under high saline conditions, FL1 population produced twice more seed compared to low salinity level. As a result, decisions on plant breeding tactics based only on screening results conducted under optimum salinity ($\approx$20 dS m^{-1}) would not guarantee a consistent result. Since considerable variability existed among

S. bigelovii populations for both salinity levels, the two salt concentrations could be used as evaluation criteria for the specific halophytic species.

14.5 Conclusions

Seawater agriculture could be more feasible as long as suitable germplasm of halophytic species of high yield potential is identified (Brown et al. 2014a). The current study was executed under field conditions in a desert environment, and germplasm with desired characteristics was distinguished. MI, SP, and GA received higher values for almost all characteristics observed, compared to LA, FL1, and FL2 populations especially under GW treatment. The first three populations constitute valuable germplasm that can go through the breeding process, in order to expand in similar hot and arid areas like UAE. However, it is worthwhile to explore the physiological functions involved in the last three populations, since they overcame the hindrance of increased salinity and led to double seed yield. The substantial genetic-based variation that existed within *S. bigelovii* wild populations facilitates the effective selection of diverse genotypes. *S. bigelovii* seems to have the potential to become a successful crop since it is tested in a climate similar to the one of its natural occurrence (Hamed et al. 2014). Several production trials have been conducted with *S. bigelovii* in Eritrea, Saudi Arabia, Kuwait, and Mexico, in order to compare the yields to other conventional crops and examine the adaptation to local climatic conditions (Brown et al. 2014a; Abdal 2009).

The study demonstrated that by targeting few traits such as spike characteristics and DTOFL, considerable improvement could be achieved in a short period. Additionally, mass selection through collection of bigger seeds could also contribute in accelerating its domestication (Brown et al. 2014a; Zerai et al. 2010). Other desirable traits that need to be taken into consideration for *S. bigelovii* cultivars are short growth cycle to avoid adverse climatic conditions, low saponin levels in seeds and vegetable tips, more uniform flowering and ripening, nematode resistance, better retention of seeds on spikes, and shorter plants that can resist lodging (Zerai et al. 2010). Finally, inbreeding would also help to receive purified lines of *S. bigelovii*.

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References

Abdal MS (2009) *Salicornia* production in Kuwait. J World Appl Sci 6:1033–1038
Aschenbach TA (2006) Variation in growth rates under saline conditions of *Pascopyrum smithii* (Western Wheatgrass) and Distichlis spicata (Inland Saltgrass) from different source populations in Kansas and Nebraska: implications for the restoration of salt-affected plant communities. Restor Ecol 14:21–27
Ashraf M (2004) Some important physiological selection criteria for salt tolerance in plants. Flora 199:361–376
Ashraf M, Athar HR, Harris PJC, Kwon TR (2008) Some prospective strategies for improving crop salt tolerance. Adv Agron 97:45–110
Ayala F, O'Leary JW (1995) Growth and physiology of *Salicornia bigelovii* Torr. at suboptimal salinity. Int J Plant Sci 156:197–205
Bailis R, Yu E (2012) Environmental and social implications of integrated seawater agriculture systems producing Salicornia bigelovii for biofuel. Biofuels 3:555–574
Brown JJ, Glenn EP, Fitzsimmons KM, Smith SE (1999) Halophytes for the treatment of saline aquaculture effluent. Aquaculture 75:255–268
Brown JJ, Glenn EP, Smith SE (2014a) Feasibility of halophyte domestication for high-salinity agriculture. In: Khan MA et al (eds) Sabkha ecosystems: volume IV: cash crop halophyte and biodiversity conservation. Springer, Dordrecht, pp 73–80
Brown JJ, Cybulska I, Chaturvedi T, Thomsen MH (2014b) Halophytes for the production of liquid biofuels. In: Khan MA et al (eds) Sabkha ecosystems: volume IV: cash crop halophyte and biodiversity conservation. Springer, Dordrecht, pp 67–72
Cassaniti C, Romano D, Hop MECM, Flowers TJ (2013) Growing floricultural crops with brackish water. Environ Exp Bot 92:165–175
Cybulska I, Chaturvedi T, Alassali A, Brudecki GP, Brown JJ, Sgouridis S, Thomsen MH (2014a) Characterization of the chemical composition of the halophyte *Salicornia bigelovii* under cultivation. Energy Fuel 28:3873–3883
Cybulska I, Chaturvedi T, Brudecki GP, Kádár Z, Meyer AS, Baldwin RM, Thomsen MH (2014b) Chemical characterization and hydrothermal pretreatment of *Salicornia bigelovii* straw for enhanced enzymatic hydrolysis and bioethanol potential. Bioresour Technol 153:165–172
Fageria NK, Stone LF, dos Santos AB (2012) Breeding for salinity tolerance. In: Fageria NK, Stone LF, Santos ABD (eds) Plant breeding for abiotic stress tolerance. Springer, Berlin, pp 103–122
Flowers TJ (2004) Improving crop salt tolerance. J Exp Bot 55:307–319
Flowers TJ, Colmer TD (2008) Salinity tolerance in halophytes. New Phytol 179:945–963
Glenn EP, O'Leary JW, Watson MC, Thompson TL, Kuehl RO (1991) *Salicornia bigelovii* Torr.: an oilseed halophyte for seawater irrigation. Science 251:1065–1067
Glenn E, Miyamoto S, Moore D, Brown JJ, Thompson TL, Brown P (1997) Water requirements for cultivating *Salicornia bigelovii* Torr. With sea water on sand in a coastal desert environment. J Arid Environ 36:711–730
Glenn E, Brown JJ, O'Leary J (1998) Irrigating crops with sea water. Sci Am 279:76–81
Glenn E, Brown JJ, Blumwald E (1999) Salt tolerance and crop potential of halophytes. Crit Rev Plant Sci 18:227–255
Glenn EP, Anday T, Chaturvedi R, Martinez-Garcia R, Pearlstein S, Soliz D, Nelson SG, Felger RS (2013) Three halophytes for saline-water agriculture: an oilseed, a forage and a grain crop. Environ Exp Bot 92:110–121
Hamed KB, Magné C, Abdelly C (2014) From halophyte research to halophytes farming. In: Khan MA et al (eds) Sabkha ecosystems: volume IV: cash crop halophyte and biodiversity conservation. Springer, Dordrecht, pp 135–142
Hester MW, Mendelssohn IA, McKee KL (2001) Species and population variation to salinity stress in *Panicum hemitomon*, *Spartina patens*, and *Spartina alterniflora*: morphological and physiological constraints. Environ Exp Bot 46:277–297

Hodges CN (2004) The seawater foundation: lessons from Africa about the world. Seawater Foundation, Tucson, AZ

Jaradat AA, Shahid M (2012) The dwarf saltwort (*Salicornia bigelovii* Torr.): evaluation of breeding populations. Int Sch Res Netw. https://doi.org/10.5402/2012/151537

Karabourniotis GA, Liakopoulos G, Nikolopoulos D (2012) Plant physiology under stress conditions. Chapter 3 salt tolerance mechanisms. Embryo, Athens, pp 57–72

Katschnig D, Broekman R, Rozema J (2013) Salt tolerance in the halophyte *Salicornia dolichostachya* Moss: growth, morphology and physiology. Environ Exp Bot 92:32–42

Khan MA, Ansari R (2008) Potential use of halophytes with emphasis on fodder production in coastal areas of Pakistan. In: Abdelly C, Ozturk M, Ashraf M, Grignon C (eds) Biosaline agriculture and high salinity tolerance. Birkhäuser, Basel, pp 157–162

Khan MA, Ungar IA, Showalter AM (2000) The effect of salinity on the growth, water status, and ion content of a leaf succulent perennial halophyte, *Suaeda fruticosa* (L.) Forssk. J Arid Environ 45:73–84

Läuchli A, Grattan SR (2007) Plant growth and development under salinity stress. In: Jenks MA, Hasegawa PM, Jain SM (eds) Advances in molecular breeding toward drought and salt tolerant crops. Springer, Dordrecht, pp 1–32

Lee G, Duncan RR, Carrow RN (2004a) Salinity tolerance of seashore paspalum ecotypes: shoot growth responses and criteria. HortSci 39:1138–1142

Lee G, Carrow RN, Duncan RR (2004b) Salinity tolerance of selected seashore paspalums and bermudagrasses: root and verdure responses and criteria. HortSci 39:1143–1147

Lee G, Carrow RN, Duncan RR (2005) Criteria for assessing salinity tolerance of the halophytic turfgrass seashore paspalum. Crop Sci 45:251–258

Lu D, Zhang M, Wang S, Cai J, Zhou X, Zhu C (2010) Nutritional characterization and changes in quality of *Salicornia bigelovii* Torr. During storage. Food Sci Technol 43:519–524

Lyra D, Ismail S, Butt KURB, Brown J (2016) Evaluating the growth performance of eleven *Salicornia bigelovii* populations under full strength seawater irrigation using multivariate analyses. Aust J Crop Sci 10:1429–1441

Martinez-Garcia R (2010) Physiological studies of the halophyte *Salicornia bigelovii*: a potential food and biofuel crop for integrated aquaculture-agriculture systems. PhD Thesis, University of Arizona

Masters DG, Benes SE, Norman HC (2007) Biosaline agriculture for forage and livestock production. Agric Ecosyst Environ 119:234–248

Munns R (2002) Comparative physiology of salt and water stress. Plant Cell Environ 25:239–250

Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59:651–681

Pandey VR, Singh PK, Verma OP, Pandey P (2012) Inter-relationship and path coefficient estimation in rice under salt stress environment. Int J Agric Res 7:169–184

Panta S, Flowers T, Lane P, Doyle R, Haros G, Shabala S (2014) Halophyte agriculture: success stories. Environ Exp Bot 107:71–83

Rozema J, Flowers T (2008) Crops for a salinized world. Science 322:1478–1480

Ruan CJ, da Silva JAT, Mopper S, Qin P, Lutts S (2010) Halophyte improvement for a salinized world. Crit Rev Plant Sci 29:329–359

Shabala S (2013) Learning from halophytes: physiological basis and strategies to improve abiotic stress tolerance in crops. Ann Bot 112:1209–1221

Shahid SA, Dakheel AJ, Mufti KA, Shabbir G (2009) Automated in-situ soil salinity logging in irrigated agriculture. Eur J Sci Res 26:288–297

Shahid M, Jaradat AA, Rao NK (2013) Use of marginal water for *Salicornia bigelovii* Torr. Planting in the United Arab Emirates. In: Shahid SA, Abdelfattah MA, Taha FK (eds) Developments in soil salinity assessment and reclamation. Springer, Dordrecht, pp 451–462

Subramanian S, Subramanian M (1994) Correlation studies and path coefficient analysis in sesame (*Sesamum indicum* L.). J Agron Crop Sci 173:241–248

Ventura Y, Sagi M (2013) Halophyte crop cultivation: the case for *Salicornia* and *Sarcocornia*. Environ Exp Bot 92:144–153

Ventura Y, Wuddineh WA, Myrzabayeva M, Alikulov Z, Khozin-Goldberg I, Shpigel M, Sagi M (2011a) Effect of seawater concentration on the productivity and nutritional value of annual *Salicornia* and perennial *Sarcocornia* halophytes as leafy vegetable crops. Sci Hortic 128:189–196

Ventura Y, Wuddineh WA, Shpigel M, Samocha TM, Klim BC, Cohen S, Shemer Z, Santos R, Sagi M (2011b) Effects of day length on flowering and yield production of *Salicornia* and *Sarcocornia* species. Sci Hortic 130:510–516

Yadav A, Kumar A, Roy C, Jaiswal JP (2013) Correlation and path-coefficient analysis for grain yield, its components and quality traits in bread wheat. Pantnagar. J Res 11:337–340

Zeng L, Shannon MC, Grieve CM (2002) Evaluation of salt tolerance in rice genotypes by multiple agronomic parameters. Euphytica 127:235–245

Zerai DB, Glenn EP, Chatervedi R, Lu Z, Mamood AN, Nelson SG, Ray DT (2010) Potential for the improvement of *Salicornia bigelovii* through selective breeding. Ecol Eng 36:730–739

Zhu JK (2001) Plant salt tolerance. Trends Plant Sci 6:66–71

Chapter 15
The Potential of Cactus Pear (*Opuntia ficus-indica* (L.) Mill.) as Food and Forage Crop

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Abstract This chapter describes the importance of cactus pear and cladodes as food and forage crop in the arid and semi-arid regions, its worldwide distribution and botanical features. The potential of cactus pear as food crop and the contribution of cactus pear fruits and cladodes in the human nutrition are highlighted. The possibilities of valorization of cactus pear to by-products, which enable high income for rural populations and the nutritional value of the fruits and young cladodes as food for human, are explained. The physiology of disease resistance in the fruits and cladodes has been discussed. The forage resources of the arid and semi-arid regions and the area of cactus pear used for animal feed in the world are presented. The physiology of disease resistance in the fruits and cladodes has been discussed. The forage resources of the arid and semi-arid regions and the area of cactus pear used for animal feed in the world are presented. The potential of cactus pear as fodder and the nutrients contents in the pads useful for animals are investigated. The possibilities of mixing pads with other fodders and food intakes developed for ruminants are suggested. The crude protein contents and minerals in the cactus pear pads have been studied in southern Morocco regarding their requirements by cows and sheep.

Keywords Food crop · Animal feed · Fodder · Human nutrition · Animal nutrition · Young cladodes

15.1 Introduction

The arid and semi-arid areas represent 30% of the total land area of the world and host more than two billion people (UNDP/UNSO 1997). They are a challenge to conventional cropping systems due to low rainfall, poor soils and elevated temperatures. The pressure on natural resources is increasing in the arid and semi-arid

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regions, and the future of these regions depend on the development of sustainable agricultural systems and the cultivation of appropriate plant species (Le Houerou 2002; Farrukh and Mufakhirah 2009). The arid and semi-arid regions will play a vital role in feeding the world in the upcoming years (Dubeux et al. 2011). The search for species that can be cultivated in the arid and semi-arid regions is of a significant importance, and the exploitation and valorization of the species growing in these areas, such as cactus pear, are necessary. Cactus pear is a highly drought-tolerant plant that can produce food and fodder at low cost (Le Houerou 2002). Seasonal and fluctuation of rainfall in arid areas reduces the potential of annual crops such as cereals and beans, and the shortage of water in these regions restricts the use of irrigation. Therefore, naturalized cultivated crops as cactus pear is a suitable alternative to produce food for humans and feed for livestock (Dubeux 2016). Cactus pear is a sustainable crop with low input demand in its cultivation for production, and both the cladodes and the fruits can be used as food for humans and animals (Reis et al. 2016).

The ecological and agricultural success of cactus pear is largely due to its crassulacean acid metabolism (CAM) which is a unique photosynthetic pathway characterized by stomata closing during the day and stomata opening during the night, with nocturne CO_2 uptake. This photosynthetic pattern provides higher water use efficiency and annual dry matter productivity than C_3 and C_4 plants (Nobel 2002). Cactus pear is considered to be the 'bridge of life' in arid and semi-arid zones due to its stems and fruits which provide feed for cattle and food for herders. It's contributing to the survival of both farmers and their animals in the arid and semi-arid regions and promising to reduce malnutrition and to improve the quality of life in those zones (FAO 2013).

One of the most interesting characteristics of cactus pear is its adaptability to arid and semi-arid climates in tropical and subtropical region in the world (from Mexico to China) due to its physiology and morphology. Its adaptability to arid conditions are related to the shape of its organs like grass pads which store water in their tissue during rainy season, and its shallow and extensive root system enables the plant to exploit scarce rainfall in arid environments (Nobel and Bobich 2002). On the other hand, isolated rainfall induces the formation of secondary roots, which increases and facilitates the uptake of water and nutrients. The cladodes are protected by a thick cuticle covered with glochids and spines. The wax in the cuticle helps plants to keep in water, reducing water loss. They have the capacity to store a great amount of water in their aquifer parenchyma, enabling the cactus pear plant to survive long periods of drought. Cladodes have few stomas per unit of surface area, and this helps to reduce plant transpiration during the day and to absorb the carbon dioxide (CO_2) which is essential for the photosynthesis process during the night. In extreme conditions of water deficiency, the stomata remain closed during both day and night, preventing transpiration and the entry of CO_2 (FAO 2013).

About 300 species of the genus *Opuntia* are known in the world, but only about 15 species are largely cultivated in the arid and semi-arid regions for their edible fruits, their young cladodes as vegetables and their pads as forage or for the cultivation of cochineal insect (*Dactylopius coccus* Costa and *Dactylopius opuntiae*

Cockerell) to produce the carmine colorant (FAO 2013). Several species of the genus *Opuntia* are grown in Mexico since pre-Columbian times for fruit production, whereas in the Mediterranean region in general, cactus pear (*O. ficus-indica*) is the most cultivated species (Barabara 2007; Chiteva and Wairagu 2013). Hernández-Urbiola et al. (2011) and Dubeux (2016) also reported that cactus pear is a multipurpose crop that provides multiple benefits for the society. It protects soil against erosion and provides feed for livestock and food for human (e.g. fruit, vegetable). It also contributes to sustainable food and feed production in countries with large areas of arid and semi-arid regions (Felker and Inglese 2003).

The prickly pear cactus is not demanding in soil. It can adapt to a wide range of soil, but prefers light and draining grounds. It fears heavy deep grounds that maintain water. An average temperature of 23 to 26 °C and full sunning are the favourable conditions for its growth and development. Cactus pear can tolerate high (up to 45 °C or more) and low (up to −5 or − 10 °C) temperatures, but for a short period of time (few days). It can be developed and grown in areas where rainfall is weak (less than 250 mm) (Kalegowda et al. 2015).

In the arid and semi-arid regions, cactus pear has taken a large importance, both in the economic and sociological levels (Beyene and Haile 2015). New plantations are established in the Mediterranean region (FAO 2013) and in Morocco in particular, where high density plantations are installed during the last two decades, in the framework of Morocco Green Plan (MGP), mainly in the southern region. The area occupied by cactus pear have evolved remarkably during the last two decades, reaching around 150,000 ha and continuous to grow within the framework of the Morocco Green Plan (MGP). There is an extension of the plantations in the producing regions, but usually with insufficient technologies to enable plants to express the totality of their potential.

Cactus pear is cultivated in the arid and semi-arid zones of Morocco on the mountainous reliefs of the southern region (Guelmim and Ait Baamrane) and on the stony grounds of the plains along the Atlantic and Mediterranean coasts and of the internal zones of Chaouia Ouardigha, Khouribga-Oued Zem, Rhamnas-Sraghnas and the Haouz of Marrakech. Average temperature in these regions varies between 12 °C in December–January and 32 °C in July–August, and the relative humidity lies between 47% in summer and 75% in winter. The majority of plantations are traditional, and the cultivation is practiced in 'bour' (under rain) and with little agricultural managements. They are not irrigated or fertilized; they have difficulties to overcome the dry and hot period of summer, which can extend from March–April to October, particularly in the southern region. Plants that are not irrigated during this hot and long period without rain are exposed to hydrous stress. The plants become yellowish, with sometimes burns on the cladodes due to heat and sunburn, sometimes associated with 'Chergui' (hot wind of the east). This hot dry period coincides with the fruit development period, which, in absence of irrigation, involves weak yields and fruits with low quality and small size.

Programmes of plantations and development of the cactus pear sector are elaborated within the MGP framework, with as main objectives the socio-economic development of the region and the generation of incomes for the farmers and rural populations. Professional organizations (PO) (co-operatives and GIE (Economic Interest Groups) are operational in the production and the marketing of cactus pear products and by-products in the region. Aligned plantations with high density are installed during this last decade, within the MGP framework, particularly in the southern area. Changes in the management practices, as the application of irrigation during the fruit development period or the hot dry period of summer, can improve the yield and fruit quality. In Ait Baamrane area (Sidi Ifni region) in the south, the cultivation of cereals is not profitable anymore because of the scarcity of rain and its irregularity in time. Cactus pear became the principal culture in the region and the development of its sector by the valorization of cactus pear to by-products showed the cactus pear effectiveness in the socio-economic development of the region.

Currently, cactus pear has known a private interest in Morocco and mainly in the southern part, due to its socio-economic importance. Cactus pear by-products are manufactured by the PO (professional organizations) and small companies. They are sold in place or in the national and international manifestations stands. The cosmetic and medicinal by-products (seed and flower oils, dermal creams, nopal powder) are sold abroad by order in the Websites of the PO and companies. Most of the PO have been supported with financial aid of the MGP or INDH (National Initiative for Human Development).

The future of arid and semi-arid areas depends largely on the agricultural systems based on species that is little demanding for water, as cactus pear. The benefits offered by cactus pear, including its adaptation to arid environments where rainfall don't exceed 100 to 200 mm make the species of first choice for the development of agricultural experiments in Morocco and in countries with large areas of arid zones. Its cultivation requires less investment, and its yield may be higher than other practiced cultures in these areas, including cereals.

The aim of this chapter is to describe the importance of cactus pear in the human and animal nutrition in the arid and semi-arid regions by describing its highly nutritive fruit and the cladodes which are used as vegetable. The potentialities of cactus pear as fodder for livestock and the use of the cladodes in animal feed will also be discussed in detail. The use of cactus pear in the production of cosmetics, pharmaceuticals, and other by-products will also be presented.

15.2 Botanical and Physiological Features, Origin, and Distribution of Cactus Pear in the World

Prickly pear or nopal cactus pear is originated from the tropical and subtropical Americas (Nobel 2002). They can be found, wild or cultivated, in a wide range of agroclimatic conditions across the world. It's native to many environments, ranging from desert areas below sea level to high altitude areas such as the tropical regions of Mexico, where temperatures are always above 5 °C, the Peruvian Andes and the areas of Canada where it can fall to −40 °C in winter (Nobel 2002). The introduction of the species in Spain probably occurred at the beginning of the sixteenth century,

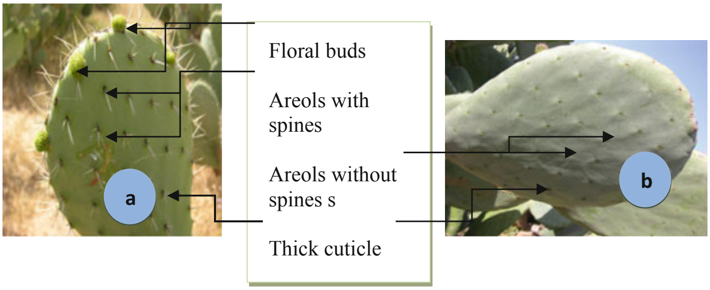

Fig. 15.1 The cladodes of cactus pear and their features; (**a**) cladode of a thorny species; (**b**) cladode of a spineless species

after the discovery of America. The plant has spread to the Mediterranean basin, Africa, Asia and Australia, where it is cultivated to provide food for humans and animals (Reis et al. 2016).

Cactus pear is a xerophytic plant, which according to new classification belongs to the family of Opuntiaceae Desv. (synon. Cactaceae Juss.). Its taxonomy is highly complex for many reasons, i.e. its phenotypes show high variability to the prevailing environmental conditions, polyploidy is common, it reproduces either sexually or asexually, and there are several interspecific hybrids (FAO 2013). Cactaceae family is composed of 1500 cactus species which comprise Mexico, Latin America, South Africa and Mediterranean countries (El-Mostafa et al. 2014). Economically, the genus *Opuntia* is the most important, as a vast number of species produce edible fruits, i.e. *Opuntia ficus-indica*. The scientific name *Opuntia* was given to the genus *Opuntia* by Tournefort in 1700 due to the resemblance of this genus to spiny plants which grow in the town of Opus in Greece (FAO 2013). The Opuntiaceae Desv. family is composed of green plants including *Opuntia ficus-indica* that often possess succulent stems called cladodes (GRIN 2007). The cladodes have an oval racquet shape that can reach 60–70 cm in height, depending on the amount of available water and nutrients (FAO 2013).

The flattened stems or cladodes act as leaves for the photosynthesis. The sides of the cladodes are covered with axillary buds which are called areoles. Areoles contain two types of spines in their cavity: the large which are modified leaves and the small hairlike prickles called glochids. They can develop flowers, new cladodes or roots. The spines and glochids can penetrate the skin when manipulating plants or fruits of the species. The leaves are often rudimentary and transitory, or absent and replaced by large spines and glochids carried by areoles. The flowers are sessile, yellow colour, hermaphrodite and solitary. They are born on the upper half of the cladode and most of them are transformed into fruits. Flowers are generally large and are born individually on the areoles. The perianth is formed by a chalice with petaloid sepals and a corolla with sepaloid petals. Stamens are numerous, while the ovary is inferior, containing 3–20 cyclic carpels (Anonymous 2006).

Figure 15.1 shows the cladodes of cactus pear with areola, spines, glochids and floral buds, and Fig. 15.2 shows the flowers and their features and the young cladodes.

Fig. 15.2 Flowers and fruits of cactus pear in the upper part of the cladode (**a**), (**b**) and (**c**) flowers and their parts (petals, stamens, ovules), and (**d**) young cladodes

The plants of the genus *Opuntia* vary between species; they differ in the shape of the cladodes, the presence or absence of spines, the size and colour of the fruit and other botanical traits. *Opuntia ficus-indica*, the true cactus pear, is the most cultivated cactus species in the world including the Mediterranean basin (FAO 2013). Its fruit pulp is sweet and juicy with variety of colours such as yellow, orange, green, red and purple (Fig. 15.3). It has various medicinal and cosmetics uses (Hernández-Urbiola et al. 2011; Dubeux 2016).

Cactus pear is an upright shrub with 3.5–5 m height. The root system is extensive and branched, with many fine absorbing roots. The length of the roots is related to the prevailing agroclimatic conditions and crop management practices, mainly the application of irrigation and fertilizers (FAO 2013). The plant often flowers once a year, but under certain climatic conditions and agronomic practices like fertilization and irrigation during the dry period of summer, the plant can flower a second time and give a late fructification in autumn (Ochoa 2003). The fruit is fleshy and ovoid having different colours with the pulp of the same hue (Fig. 15.3). The pulp contains many seeds which are eaten with the pulp. The epidermis of the fruits includes areoles with abundant yellow glochids (Mondragon Jacobo 2004).

Fig. 15.3 Cactus pear fruits of three different varieties in southern Morocco: (**a**) variety 'Aissa', (**b**) and (**c**) cv 'El Akria' and (**d**) and (**e**) variety 'El Bayda'

In Mexico, the total area occupied by the cactus pear is around three million hectares (ha), including more than 70,000 ha under cultivation. Brazil is a major producer of cactus pear, where it is cultivated on about 500,000 ha of land (Santo-Ares et al. 2009). Inglese (2010) reported around 3000 ha for commercial production in Italy, 25,000 ha in Tunisia and more than 1000 ha in each in Chile, Argentina and South Africa. In Morocco, the area for cactus pears planting has evolved remarkably during the last two decades, reaching around 150,000 ha and continuous to grow within the framework of the Moroccan Green Plan.

Cactus pear is known by different names in different countries. It's known as 'Tuna' in Mexico, 'higo de las Indias' (Indian fig) in Spain, 'fico d'India' in Italy, 'figue de Barbarie' in France, 'palma forrageira' in Brazil, 'beles' in Ethiopia and 'prickly pear' in the United States, South Africa and Australia. The term 'prickly pear' is evolved into the name cactus pear to replace the word 'prickly' which means with spines (FAO 2013).

15.3 The Potential of Cactus Pear (*Opuntia ficus-indica*) as Food Crop

Cactus pear serves as a source of food and feed and a means of additional income to rural populations in the arid and semi-arid regions of the world. It resists high temperatures and long periods of drought, which makes it suitable for food and forage production in the arid and semi-arid areas (Gebreegziabher and Tsegay 2015). Cactus pear is widely cultivated for its high-quality fruits that have variety of colours making it attractive to the consumers. In Mexico, it is grown for its young cladodes as vegetables, where it is very popular and called ‘nopalitos’. They are consumed as vegetable when they are young (3–4 weeks in age) and tender, using different cooking methods. When the plants are 1 year to 2 years old, they can be used for the fruit production. After 2 years, the cladodes can be used in animal feed, powder making and other products (FAO 2013).

The edible parts of cactus pear are the young cladodes, flowers and fruits. The fruits are eaten fresh, boiled or grilled. They are also used in juice, syrup or jam production. The young cladodes can be consumed fresh or bold, but during the last decades, research studies on cactus pear have produced other alternatives for processing and valorizing cactus pear fruits and cladodes (FAO 2013). Fruits and young cladodes contribute to human food. They can be considered as a source of income for low-income inhabitants of the arid and semi-arid regions. Many industries use cactus pear fruits and cladodes for the production of foods, food additives, cosmetics, pharmaceuticals and alcoholic drinks (Kuti 2004; Shi et al. 2004). Its fruits are also dried in sun to make cactus pear raisins. The plant is also used to combat desertification (Chiteva and Wairagu 2013). There are many possibilities of making by-products from cactus pear fruits and cladodes, and these prospects open a considerable number of opportunities to arid and semi-arid regions (FAO 2013).

The young cladodes can be produced fast and abundantly under arid conditions and with little amount of water, which is not suitable for the production of other vegetables. In Mexico, the country of the species origin, intensive orchards of cactus pear provide fruit and young cladodes for human consumption (Griffith 2004). In these orchards, general agronomic practices mainly irrigation, fertilization, pruning and control of pests and diseases are used. In Italy, intensive orchards for fruit production are grown. In North Africa, the major uses of cactus pear include fruit production and feed for livestock, while medicinal and cosmetic industries based on cactus pear are emerging. In South Africa, cactus pear is traditionally used for fruit production (De Waal et al. 2013). In South America, Chile and Argentina grow most of the cactus for fruit production, and medicinal and cosmetic industries, while Peru has an intensive cochineal cultivation for red dye production (Dubeux 2016).

In south of Morocco, several co-operatives are currently involved in the production of cactus pear by-products, agri-food products (jam, juice, young cladodes cans), cosmetics (natural seed oil, dermal creams, soaps, shampoos, etc.) and pharmaceuticals (dried pads powder or nopal powder, dried flowers, etc.), and a considerable number of these co-operatives have benefited from a financial support

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Fig. 15.4 By-products of cactus pear (jam, juice, cans) of young cladodes, nopal powder, dried flowers, natural seed oil, soap from a Moroccan co-operative which has received a financial support from the INDH (National Initiative for Human Development). Photo credit Magazine of tourism and sustainable development in Morocco

from the PMV (Moroccan Green Plan) or the INDH (National Initiative for Human Development) (Fig. 15.4)

Cactus pear fruits are appreciated for their characteristic taste and aroma as well as their dietetic properties. They are classified according to their shape (round, elliptic, ovoid or oblong), and the shape is an important criterion for its commercial value. Cactus varieties with ovoid or oval shape and large fruit size have more commercial value than the others. Oval fruits are easier to handle during the harvest, hence rendering less damage to the upper part of the cladodes (Gebreegziabher and Tsegay 2015). Cactus pear fruit quality is based on sugar content, peel colour, fruit weight, pulp weight and seed content (Kader 2002). The varieties with lower number of seeds in their fruits are commercially more acceptable because they contain more pulp tissue. The development of varieties with less seeds is one of the most important breeding objectives in cactus pear (Gebreegziabher and Tsegay 2015). Glochids on cactus pear fruits are easy to remove by mechanical brushing (Felker et al. 2005).

Pulp yield is a crucial factor for food production, and the quantity of peel and pulp in cactus fruit varies according to the zone of cultivation. For *Opuntia ficus-indica* in Chile, the proportion of peel is 50.5 g $(100\ g)^{-1}$ of pulp and 49.6 g $(100\ g)^{-1}$ of edible components (pulp and seeds) of which 78.9 g $(100\ g)^{-1}$ is pulp and 20.1 g $(100\ g)^{-1}$ is seeds. For the same species in Saudi Arabia, the proportion of pulp is 88 g $(100\ g)^{-1}$ and that of seeds is 12 g $(100\ g)^{-1}$ of edible part. In Argentina, the percentage of pulp is 54.7 g $(100\ g)^{-1}$ and 42.3 g $(100\ g)^{-1}$ of peel and seeds (FAO 2013).

Table 15.1 Physicochemical features of the fruits of cactus pear cultivars in Morocco

Physicochemical characters of the fruits at ripening stage	Cultivars			
	'Moussa' cv. in Sidi Ifni area	'Moussa' cv. in Agadir area	'Mles' cv. in Khouribga area	'Aissa' cv. in Agadir area
Fruit length (cm)	6.49 ± 0.16	7.14 ± 0.1	6.67 ± 0.2	7.24 ± 0.1
Fruit diameter (cm)	4.92 ± 0.16	5.02 ± 0.1	4.52 ± 0.1	5.27 ± 0.04
Fruit weight (g)	81.37 ± 2.22	122 ± 3	66.31 ± 3.84	135 ± 2
Pulp weight (g)	48.65 ± 0.87	67.2 ± 1.3	39.14 ± 3.47	72.6 ± 1.5
Peel thickness (cm)	0.41 ± 0.07	0.18	0.35 ± 0.03	–
Dry weight of 100 g pulp	21.8 ± 0.36	–	–	–
Content of juice	18.82 ± 0.40 (ml/ 100 g pulp)	71.14%	49.9 ± 2.8%	70.44%
Content of sugars	14.43 ± 0.28 (g/l juice)	56.78%	12.5 ± 0.5 °Brix	52.47%
Titratable acidity (TA)	–	52.47 g/l	0.069% ± 0.005	0.61 g/l
pH	–	6.10		6.12
Vitamin C (mg/ 100 g pulp)	–	–	17.3 ± 1.1	–
Fertile seeds	3.65 ± 0.05 (/g fresh pulp)	–	70.22 ± 5.94%	–
Aborted seeds	1.46 ± 0.13 (/g fresh pulp)	–	29.78 ± 5.94%	–

The physiochemical characters of the fruits of some varieties in Morocco are presented in Table 15.1.

Several studies have shown that rain or application of water by irrigation during the fruit development period increase fruit yield and fruit sizes (fruit weight and fruit dimensions) (van der Merwe et al. 1997; Felker et al. 2002; Barabara 2007; Varela-Gamez et al. 2014; Arba 2017), while the other experiments (Mulas and D'hallewin 1997; Gugliuzza et al. 2002) have indicated that irrigation of cactus pear during this period increases the yield, but has no effect on the calibre of the fruits or on their organoleptic contents. Studies carried out on the fertilization of cactus pear also showed that application of nitrogen and phosphorus fertilizers has a significant positive effect on fruit and biomass yields and fruit size (Sangati et al. 2014; Zegbe et al. 2014; Da Silva et al. 2016; Arba et al. 2017). Some other authors have shown that fertilization had no effect on the organoleptic quality of the fruits (Jorge zegbe et al. 2014, Da Silva et al. 2016), while others have indicated that fertilization had a positive effect on these characters, including the titratable acidity, the sugar contents and vitamin C (Sangati et al. 2014). Zegbe et al. (2014) have reported that potassium fertilizer has no effect on fruit yield.

The nutritional value of cactus pear fruit is similar to the other fruits including apple, apricot, cherry, melon and peach. Its content in soluble solids is high, and this makes it suitable for processing, as its high sugar contents are good for preservation. The most sugars in cactus pear fruits are reducing sugars with about 53% glucose and the remaining fructose. Glucose in cactus pear fruits is in a free form that can be absorbed directly by the body. Fructose is also easily absorbed by the body. It also helps to improve flavour of the fruit. The cactus pear fruits are important source of many nutrients including protein (0.21–1.6%), fat (0.09–0.7%), fibre (0.02–3.15%) and ash (0.4–1.0%). The calorific value of the fruit pulp varies between 31 and 50 kcal $(100\ g)^{-1}$. The amino acid content in cactus pear fruits is 257.24 mg $(100\ g)^{-1}$. Cactus pear fruits have a high level of ascorbic acid [40 mg $(100\ g)^{-1}$]. They are a good source of minerals such as potassium (217 mg $(100\ g)^{-1}$), calcium [15.4–32.8 mg $(100\ g)^{-1}$] and phosphorus [12.8–27.6 mg $(100\ g)^{-1}$]. Cactus pear fruits are low in sodium (0.6–1.19 mg $(100\ g)^{-1}$) and that is beneficial for people with kidney problems and hypertension (FAO 2013).

Young cladodes are an excellent source of proteins and vitamins, as several authors reported high levels of amino acids (proline, taurine and serine) in them (Stintzing et al. 2001; Piga 2004; Stintzing and Carle 2005). Like many other vegetables, young cladodes of cactus pear contain 90% water and 3.5% fibre. It is a popular vegetable in Mexico and the southern United States where a large number of people are Mexican-American. Young cladodes of cactus pear are part of the basic diet of the populations of these countries. Its nutritional value is comparable to lettuce and spinach, while its dietary fibre is similar to other fruits and vegetables, such as mango, melon, apricot, grapes, spinach, artichoke, broccoli and radish (FAO 2013). Cactus pear is rich in minerals, mainly calcium (93 mg $(100\ g)^{-1}$) and potassium (166 mg $(100\ g)^{-1}$). Young cladodes contain moderate amounts of carotenoids (30 μg $(100\ g)^{-1}$) and vitamin C (11 mg $(100\ g)^{-1}$), as it is low in fat (0.3%), carbohydrates (5.6%) and sodium (2 mg $(100\ g)^{-1}$), which makes it a healthier vegetable (Saenz 2004; Saenz et al. 2004).

Chemical analysis of young cladodes, mature pads and lignified ones showed that the protein contents are higher in the young cladodes, while the fibre contents increased with the age: 8% in the young to 16.1% in the lignified pads. The ash contents also increased with the age of cladodes (Tegegne 2002).

In addition to the nutritional value of foods, the recent trend in consumer demand is the health benefits including disease prevention (Saenz 2004). Fruits and cladodes of cactus pear contain functional traits or compounds which help to fight diseases. The functional traits are fibre, mucilage, pigments (betalains and carotenoids), minerals (calcium and potassium) and vitamins, mainly vitamin C. They can enhance health and help to prevent or to treat different diseases (high cholesterol in the blood, obesity) for their contribution to a healthy diet (Sloan 2000; Saenz 2004). Among these functional characteristics, fibre is the most studied trait as it's an important element in the nutritional value of cactus pear fruits and cladodes. The fibre helps in controlling cholesterol and the treatment of diseases like diabetes and obesity. The components of dietary fibre are cellulose, hemicelluloses and lignin (FAO 2013).

Currently, the demand for natural ingredients and health promoting foods is increased. Cactus pear fruits and cladodes open new hopes for the arid and semi-arid regions due to the sustainability in terms of production of cactus pear in these regions. Cactus pear medicinal properties are known since a long time. The plant was used as an anti-inflammatory, diuretic and antispasmodic agent. Like young cladodes, cactus pear flowers can be eaten as vegetable. Some flower components are useful in combating benign prostatic hyperplasia because extracts of dried flowers have given beneficial effects. The cladodes are a reliable source of fibre, an important element for the human diet and of considerable potential for medical use. The dried pads have been considered as one of the functional food by including essential ingredients, i.e. fibres, amino acids, carbohydrates, vitamin C and minerals. Cactus pear is well-known for its anti-diabetic and lipid-lowering properties. It's also very useful in obesity, colitis, diarrhoea and the prostatic benign hypertrophy (FAO 2013).

Cactus pear contains a variety of nutrients and bioactive properties that are beneficial for human health. The compositions of pads and fruits are different, but both provide macronutrients, vitamins, minerals and phytochemicals (Bauman and Ashley 2015). The fruits are rich in antioxidant pigments called betacyanins (Castellar et al. 2003) which found to reduce cholesterol levels and low-density lipoprotein (LDL) (Tesoriere et al. 2004). The pads contain manganese which is essential for the metabolism of the glucose (Emsley 2011) and magnesium that helps the body to regulate the synthesis of protein, the muscle function and the blood pressure (Bauman and Ashley 2015). The use of cactus pear for the diabetes treatment has been cited by many authors. Rats with induced diabetes feeding pads powder followed by glucose were found to have a reduced level of glucose (Nuñez-López et al. 2013). A reduction of 40% in blood sugar was also reported in rats feeding on nopal powder and 30% reduction in rats feeding young cladodes powder. These results suggest that the maturity of pads influence the lowering of blood sugar and the fibre could have an important role in lowering the blood sugar by delaying the absorption of carbohydrates in the food. Galati et al. (2003) also reported that rats feeding on concentrated juice of cactus pear fruits were found to be protected against the formation of ulcer.

The anti-diabetic properties of cactus pear have also been explored in humans. A recent study on type 2 diabetics showed that consumption of steamed young cladodes significantly reduced the levels of blood glucose and serum insulin one hour after taking a high carbohydrate breakfast (López-Romero et al. 2014), as well as substantial decrease in the hormone, which stimulates the insulin production (Bauman and Ashley 2015). In prediabetics, a product formulated with both cladode and fruit peel of cactus pear has been found to reduce blood glucose (Godard et al. 2010). The cladodes of cactus pear contain elevated levels of calcium which have been studied for their effects on bone mineral density. After daily consumption of 55 g of dehydrated nopal, the level of calcium in urine decreased and bone mineral density increased in women 35 to 55 years old (Aguilera-Barreiro et al. 2013). Premenopausal women consuming 15 g of dehydrated nopal also had increased bone mineral density of the lumbar spine region (Guevara-Arauza et al. 2013). The oilseed of cactus pear also reduces blood glucose and total cholesterol, and some of antiviral properties have also been noted in it (Chauhan et al. 2010).

Another interesting product that can be manufactured from cactus pear is the powder which is obtained from its dried pads. The powder of cactus pear pads or nopal powder is an excellent element in the nutritional food for human body because it includes fibre (more than 50%), vitamins and minerals. These vitamins and minerals help our body to detoxify and to reduce level of blood sugar and cholesterol. For this reason, nopal powder is an appetizing which helps obese people to reduce their weight. Some studies have suggested that the nopal powder stabilizes and regulates the blood sugar in the body (FAO 2013).

The flowers of cactus pear are used in cosmetic and as food colours. Apart from seed oil, it has another type of oil, which can be extracted from the maceration of flowers. Both seed and flower oils are healthy and have suitable properties. Macerated oil from the flowers is offered as 'cactus pear flower oil' but not as 'cactus pear seed oil' which offers a high amount of essential fatty acids and contains more than 88% of unsaturated fatty acid with a proportion of approximately 70% of linoleic acid (Omega 6 fatty acid) (FAO 2013).

15.4 The Potential of Cactus Pear (*Opuntia ficus-indica*) as Forage Crop

Rangelands in arid and semi-arid regions are usually the basis of the livestock production system. The productivity of a rangeland is usually low [<5 t DM (dry matter) ha^{-1} $year^{-1}$], with lower potential of forage (<1 t DM ha^{-1} $year^{-1}$ of consumable forage) leading to less feeding capacity (12–15 ha to sustain an adult cow). The global population of livestock has increased sharply in the past decades leading to rangeland degradation in different areas of the world. Water shortage is a major factor in arid areas that limits the agriculture and livestock production there (Dubeux et al. 2015). The forage resources are limited in the arid and semi-arid regions, and the green fodder is scare in these areas, mainly during the dry summer (Tafere 2016). The Mediterranean region, particularly inland areas, also has been suffering from severe drought during long summers. The search for drought-tolerant fodder species is needed for a better sustainable animal production in the drought-prone regions. Cactus pear could be an important forage crop for livestock in the arid and semi-arid regions due to its drought tolerance, high biomass yield and palatability. It could be the main food source during the dry season in the arid and semi-arid areas when the alternative of crop residue is not present in these areas. In many of the arid and semi-arid regions, cactus pear is harvested from both wild and cultivated plantations to feed animals. All types of livestock (cattle, sheep, goats, camels and horses) are reported to consume cactus pear (Tafere 2016). The fruits and pads of cactus pear have nutritional and economical value that provides energy, water, and minerals to both human and animals (Andrade-Montemayor et al. 2011; Rodrigues et al. 2016).

Cactus pear has a production potential of more than 20 t DM ha^{-1} year^{-1} and provides 180 t ha^{-1} year^{-1} of good quality water stored in its pads for livestock (Dubeux et al. 2015). This is at least 60 times higher than the rangeland productivity and is enough to produce forage to sustain five adult cows per year. Thus, with small intensive cactus pear orchards, it's possible to produce feed for livestock and reduce the degradation of rangelands. The potential of cactus pear is still underexploited; the estimated surface occupied by cactus pear is less than 0.1% of the dry land area used as grasslands. The making of silage using local resources is also a better approach to reduce wastage of forages, and these resources could be used to feed animals during the scarcity periods of dry season. Also, other opportunities exist by converting fruits and vegetables wastes to animal feeds (Dubeux 2016).

In Mexico, an estimated three million ha of cactus pear are extensively cultivated to feed animals. Brazil has one of the largest areas of cactus pear devoted to feed livestock (De Farias Ramos et al. 2015). The cultivation of cactus pear in this country constitutes a potential food source for animals during the dry season in its semi-arid region due to the crop's high potential for phytomass production (Oliveira et al. 2007; Tegegne et al. 2007; Silva et al. 2014). Animal production is one of the most important options for this region. It is one of the main factors that ensure food security, creation of jobs and income for rural families in the Brazilian semi-arid region (De Farias Ramos et al. 2015). Cactus pear is widely incorporated in the process of production of this region due to its water use efficiency and nutritional value (Sales et al. 2009). Currently, in South Africa, livestock production is replacing some of the fruit orchards (de Waal et al. 2013).

Cactus pear pads provide water, vitamins, carbohydrates and calcium that are required in the animal diet (Rodriguez-Garcia et al. 2007). They are attractive as food due to their efficiency in converting dry matter and thus provide digestible energy (Gebremariam et al. 2006). Cactus pear pads are easily consumed by animals (Fig. 15.5) which preferred them to straw. Dry matter intake (DMI) of the pads increased with their assimilation (Gebremariam et al. 2006). Watering animals during summer and drought periods is a serious challenge in arid and semi-arid zones, and the high content of water in cactus pear pads could solve the problem in these regions (Nefzaoui and Ben Salem 2002; Gebremariam et al. 2006; Costa et al. 2009; Gebreegziabher and Tsegay 2015). Cactus pear could be a supplement for low-quality fodder such as straw, and the combination of the two could be an alternative feed for the nutrition of small ruminants in the arid and semi-arid areas (Gebremariam et al. 2006). Food intakes based on cactus pear pads and other fodder elements are developed for sheep in North Africa (Table 15.2).

Several authors reported that the fibre content in the cactus pear pads is lower than in the basic feed (Mengistu 2001; Nefzaoui and Ben Salem 2002; Gebremariam et al. 2006). Mengistu (2001) reported that the content of NDF (neutral detergent fibre) in cactus pear pads is for 241 g kg^{-1} DM, while Nefzaoui and Ben Salem (2002) reported 255 g kg^{-1} DM. Forages with high fibre contents have poor DMI due to their high rumen effect and low digestibility. According to Taddesse et al. (2014), the crude protein (CP) in dried, chopped and grounded cactus pads is 61.3 g kg^{-1} DM, which is lower than in the hay (67.5 g kg^{-1} DM). However, the CP in each of

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Fig. 15.5 Consumption of cactus pear pads by cattle. Photo credit J C Dubeux

Table 15.2 Food intakes based on cactus pear pads and other fodder elements developed for sheep in North Africa

Fodder element	Food intakes developed in Morocco (Chriyâa 1998)				Food intakes developed in Tunisia (Nefzaoui and Ben Salem 2000)			
	R1	R2	R3	R4	g DM/day	R1	R2	R3
Cactus pear (kg FM/day)	2.5	3.5	5.5	4.5		197	353	550
Atriplex (kg FM/day)	1.5	1.0	0.6			554	391	236
Straw (g/day)	200	200	200	600		160	159	167
CMV (g/day)	30	30	30	30				

FM fresh matter, *DM* dry matter, *CMV* vitaminized mineral supplement

the following feeds, cactus pear + *Acacia saligna* (Labill.) Wendl. (82.3 g kg^{-1} DM), cactus pear + *Acacia robusta* Burch. (127.9 g kg^{-1} DM) and cactus pear + *Sesbania sesban* (L.) Merr. (185.7 g kg^{-1} DM), is much higher than that of hay and cactus pear pads. High organic matter (OM), NDF and acid detergent matter (ADF) were found in the hay than in cited feeds. The cactus pear pads have the high ash contents (280.5 g kg^{-1} DM) (Taddesse et al. 2014). The chemical composition of cactus pear pads and other fodders including straw, hay and atriplex are presented in Table 15.3.

Tafere (2016) reported more NFD (387.6 g kg^{-1} DM) and acid detergent lignin (ADL) (48.9 g kg^{-1} DM) in cactus pear pads than other authors (289 g kg^{-1} DM for NFD and 40 g kg^{-1} DM for ADL) (Costa et al. 2013). However, he reported lower ADF content (199.9 g kg^{-1} DM) than that of other authors (219 g kg^{-1} DM) (Amare et al. 2009). Cactus pear pads have high contents of carbohydrates, water and ash, but less amounts of DM, CP, NDF, ADF and ADL, whereas the straw contains high contents of NDF, ADF, ADL and CP (Tafere 2016).

Table 15.3 Chemical composition of cactus pear pads in comparison with other fodders (Chriyâa 1998)

Fodder element	Crude proteins	ADF	NDF	Digestibility in vitro
	% dry matter			
Cactus pear pads	4.8	27.5	15.8	78.7
Wheat straw	5.2	69.6	42.4	45.5
Alfalfa hay	13.8	47.1	31.3	59.4
Atriplex	13.4	34.2	14.4	63.1

The preferences in palatability of cactus pear pads by different animals are similar to cactus pear fruits by humans. In Ethiopia, for example, the varieties 'Limo' and 'Kille' are the most, while 'Cheguar' and 'Chewchawa' are the least palatable for all the livestock types (Gebreegziabher and Tsegay 2015). These authors also reported use of cactus pear as human food, animal feed, live fence and other purposes, though it is mostly used as forage in Ethiopia.

15.5 The Nutrient Contents of Pads in Different Cactus Pear Varieties

Gebreegziabher and Tsegay (2015) reported that dry matter content in cactus pear pads of different varieties in Endamehoni district in north Ethiopia varied between 11.04% and 14.04%. The ash content in pads of these varieties varied between 20.15% and 22.79%, and the organic matter (OM) content ranged between 77.21% and 79.85%, while the crude protein (CP) content varied between 5.38% and 6.02%. The average CP content in South African cactus pear varieties is 5.5% (Mciteka 2008). For Mexican varieties, an average value of 5.4% of CP for the pads of 1 year and 4.2% for the 2-year-old pads have been reported (Gebreegziabher and Tsegay 2015). Tegegne (2001) found that some other varieties in another Ethiopian district are moderate in CP in relation to diet requirements of ruminants. He reported an average of 9.15% CP for the 2-year-old pads, which is higher than the varieties reported by Gebreegziabher and Tsegay (2015). The difference could be due to the nature of the selected area, the soil type, topography, climate and harvesting time. Moreover, the CP content of the varieties in Endamehoni district is less than the 7% requirement for efficient ruminant function. Gebreegziabher and Tsegay (2015) also showed that feeds with high content of protein are considered as high quality fodders. The average water content in pads of the Endamehoni district varieties is 90%, and for the South African varieties it is about 91% (Mciteka 2008). The high content of moisture in cactus pear pads could hamper the dry matter intake (DMI) by animals. The DMI could be increased if the fresh cladodes are wilted or dried before feeding. Younger cladodes have the highest moisture content and are more palatable due to their low fibre content. Animals consume more DM in the form of hay compared to wet material (Gebreegziabher and Tsegay 2015).

Table 15.4 The minerals contents in pads of cactus pear *Opuntia ficus-indica* (L.) Mill. cvs. 'Aissa' and 'Moussa' in Sidi Ifni area and in the experimental station of the Horticultural Complex, IAV Hassan II, in Agadir area

Mineral elements	cv 'Moussa'		cv 'Aissa'		Level of significance
	Locality Zlaguim in Sidi Ifni area	Locality IAV Hassan II in Agadir area	Locality Ahl Haymad in Sidi Ifni area	Locality IAV Hassan II in Agadir area	
N (%)	1.50 ± 0.08	1.03 ± 0.12	1.33 ± 0.10	0.86 ± 0.04	*
CP (%) (%N × 6.25)	9.37	6.43	8.31	5.37	
P (%)	0.20 ± 0.02	0.092 ± 0.00	0.090 ± 0.00	0.084 ± 0.01	**
Ca (%)	5.12 ± 0.35	4.78 ± 0.33	3.99 ± 0.79	4.26 ± 0.54	ns
Na (ppm)	11 ± 0.10	11 ± 0.20	12 ± 0.30	15 ± 0.30	*
Mg (%)	0.24 ± 0.05	0.30 ± 0.08	0.22 ± 0.04	0.22 ± 0.03	**
K (%)	0.65 ± 0.03	0.52 ± 0.08	0.45 ± 0.10	0.56 ± 0.05	ns

ns no significant difference; * significant difference at $p < 0.05$; ** significant difference at $p < 0.01$

In southern Morocco, the mineral contents in cactus pear pads were also different between varieties and localities (Table 15.4) due to variations in soil and climatic conditions among regions and locations (Arba 2013). The results showed that the CP content in the cactus pear pads cv 'Moussa' in Sidi Ifni area (9.37%) met the CP requirement of dairy cows [9.2% (NRC 1976)] and the CP content of the same variety in Agadir area (6.43%) met the requirement of dry cows (5.9%). The cactus pear cv 'Aissa' met the requirement of cows in Sidi Ifni area (8.31%), and both cultivars met those of sheep [0.21–0.99% (NRC 1985)] and goats [0.05–0.46% (NRC 1981)] in both areas (5.37–9.37%). A low CP content in cactus pear pads could be improved by an application of N fertilizer or by adding or combination with another source of fodder. Phosphorus fertilization can increase the level of the mineral in the pads.

Phosphorus (P) and some other nutrients, mainly calcium (Ca) and potassium (K), are important in the animal diet. The cultivar 'Moussa' has P level adequate for dry cows [0.18% (NRC 1976)] in Sidi Ifni area (0.20%) but not enough for them in Agadir area (0.092%), and variety 'Aissa' has P level which is not sufficient for these cows in both regions (0.090% in Sidi Ifni area and 0.084 in Agadir area). However, both cultivars have P concentration, which is recommended for sheep (0.004–0.020%) and goats [0.002–0.013% (NRC 1981, 1985)] in both areas (0.084–0.20%). Average P in cactus pear pads in Tunisia is 0.04% (Nefzaoui and Ben Salem 2000). Ca concentration in 'Moussa' of both areas is higher than that of 'Aissa', and Mg in 'Moussa' in the same areas is also higher than that of 'Aissa' (Table 15.4). The difference is due to the nature of soils where the two cactus pear varieties were planted. Moussa was grown in soil, which contains more Ca but less amount of Mg, while for Aissa it's vice versa (Table 15.5). According to the chemical analysis, soils of both areas are rich in Mg and Ca that exceeds 7%.

Table 15.5 Chemical composition of the soil in two localities of Sidi Ifni area (Zlaguim and Ahl Haymad) and the experimental station of the Horticultural Complex, IAV Hassan II, in Agadir area

Mineral elements	cv. 'Moussa'		cv. 'Aissa'		Level of significance
	Locality Zlaguim in Sidi Ifni area	Locality IAV Hassan II in Agadir area	Locality Ahl Haymad in Sidi Ifni area	Locality IAV Hassan II in Agadir area	
N (%)	29.50 ± 7.35	26.50 ± 1.91	28.00 ± 7.26	25.50 ± 4.20	ns
P (ppm)	0.06 ± 0.02	0.02 ± 0.00	0.02 ± 0.01	0.02 ± 0.00	**
Active calcium (%)	7.75 ± 1.32	11.00 ± 0.24	5.45 ± 0.83	11.13 ± 0.62	**
Ca (ppm)	1.26 ± 0.05	1.29 ± 0.04	1.31 ± 0.06	1.30 ± 0.05	*
Na (ppm)	0.08 ± 0.03	0.11 ± 0.01	0.12 ± 0.04	0.12 ± 0.01	*
Mg (ppm)	0.73 ± 0.04	0.75 ± 0.07	0.67 ± 0.07	0.76 ± 0.07	ns
K (ppm)	0.23 ± 0.04	0.18 ± 0.06	0.24 ± 0.06	0.19 ± 0.05	ns

ns no significant difference; * significant difference at $p < 0.05$; ** significant difference at $p < 0.01$

Thus, both cultivars exceed Ca and Mg requirements of cattle in both areas [0.18–0.44% Ca and 0.04–0.18 Mg (NRC 1976)]. Different studies show that average Ca concentration for *Opuntia ficus-indica* is 8.66% in Tunisia (Nefzaoui and Ben Salem 2000) and 3% in Texas, USA (Gonzalez 1989).

The level of Na in 'Aissa' is higher than that of 'Moussa' in both regions (Table 15.4) because of higher level of Na in soils where 'Aissa' was cultivated (Table 15.5). Nevertheless, both cultivars did not meet Na requirements of cattle [0.06% (NRC 1976)] in both areas, but deficiency in this element could be compensated by adding Na to drinking water or by putting salt rock in front of cattle to lick it like as it's done by most of cattle breeders in Morocco. For K, 'Moussa' met the cattle requirement [0.6–0.8% (NRC 1976)] in Sidi Ifni area (0.65%). Comparison of the two cultivars in Agadir area showed that for N, P, Ca and Mg, 'Moussa' (1.03, 0.092, 4.78 and 0.30%, respectively) is higher than 'Aissa' (0.86, 0.084, 4.26 and 0.22%). Soil analysis (Table 15.5) showed that except for nitrates, in Moussa's planting area, the contents of P, Ca and Mg are either similar or higher than that of Aissa's locale. The analysis shows that these elements concentration in 'Moussa' is higher than in 'Aissa'. Na and K concentration in 'Aissa' (15 ppm and 0.56%, respectively) are higher than those in 'Moussa' (11 ppm and 0.52%, respectively) (Table 15.4), and chemical analysis (Table 15.5) showed that the Na and K contents in soil where 'Aissa' was planted are higher than that the Moussa's location. That explains the higher concentration of K and Na in 'Aissa' than in 'Moussa'.

15.6 Conclusions

Cactus pear is a food and fodder crop adapted to arid and semi-arid environments. The widespread use of cactus pear in the arid and semi-arid regions is attributed to its drought resistance, cultural acceptability, efficacy in animal and human feed and economic affordability. Cactus pear has a potential to produce higher yields, which is even better than the C_4 grasses in more humid and hot environments. It may serve as a source of income for the rural populations in the arid and semi-arid regions. The possibilities of obtaining by-products from cactus pear fruits and cladodes and the sustainability of production of cactus pear in these regions open a considerable number of opportunities and hopes. Cactus pear fruits and cladodes are important in the human food and animal feed due to their nutritional value and their high contents in nutrients. The nutritional value of the fruits is similar to other fruits (apple, pear, orange, apricot) with higher soluble solids contents. Young cladodes are rich in fibre and minerals, mainly calcium, which is important in the human consumption. In addition to their nutritional value, cactus pear fruits and cladodes also have medicinal properties, which help to prevent or to treat different diseases.

The forage productivity in a rangeland of the arid and semi-arid regions is usually low, and the forage resources are limited in these areas. Cactus pear is an important forage crop for livestock in these regions due to its drought resistance, high biomass yield and palatability. It's consumed by all types of livestock (cattle, sheep, goats, camels and equines). Animal production is one of the main factors that ensure food security, job opportunities and income for rural families in the arid and semi-arid regions. It's rich in carbohydrates with high digestibility, but low in crude proteins and neutral detergent fibre (NDF). Cactus pear is not a complete feed source, but it could be a supplement for low-quality fodder such as straw, and the combination of the two could be an alternative feed for the ruminants of the arid and semi-arid regions.

References

Aguilera-Barreiro M, Rivera-Márquez JA, Trujillo-Arriaga HM et al (2013) Intake of dehydrated nopal (*Opuntia ficus-indica*) improves bone mineral density and calciuria in adult Mexican women. Food Nut Res 57:19106–19115

Amare D, Melaku S, Berhane G (2009) Supplementation of isonitrogenous oil seed cakes in cactus (*Opuntia ficus-indica*)-tef straw (Eragrostis tef) based feeding of Tigray highland sheep. Anin Feed Sci Technol 148(2–4):214–226

Andrade-Montemayor HM, Cordova Torres AV, García-Gasca T et al (2011) Alternative foods for small ruminants in semiarid zones, the case of Mesquite (*Prosopis laevigata* spp.) and Nopal (*Opuntia* spp.). Small Rumin Res 98:83–92

Anonymous (2006) Field botany at Williams College. Williams College

Arba M (2013) Nutritive value of cactus pear for cattle in South of Morocco. Acta Hortic 995:303–307

Arba M (2017) Effets de la fertilisation NP et de l'irrigation à des périodes critiques sur le rendement et la qualité des fruits du figuier de Barbarie (Opuntia ficus-indica (L.) Mill.). Thèse de doctorat en sciences agronomiques et ingénierie biologique. Université de Liège, Gembloux Agro Bio-Tech, Belgique

Arba M, Falisse A, Choukr-Allah R, Sindic M (2017) Effects of nitrogen and phosphorus fertilization on fruit yield and quality of cactus pear Opuntia ficus-indica (L.) Mill. Fruits 72 (4):212–220

Barabara K (2007) Characterization of Cactus Pear germplasm in South Africa. PhD. thesis, University of the Free State, Bloemfontien, South Africa

Bauman H, Ashley S (2015) Food as medicine: Prickly Pear Cactus (*Opuntia ficus-indica*, Cactaceae). HerbalEGram 12(9):1–8

Beyene HD, Haile RG (2015) Agro-industrial use of cactus, a review. Food Sci Qual Manag 39:26–30

Castellar R, Obón J, Alacid M et al (2003) Color properties and stability of betacyanins from *Opuntia* fruits. J Agric Food Chem 51(9):2772–2776

Chauhan SP, Sheth NR, Jivani NP et al (2010) Biological actions of *Opuntia* species. Syst Rev Pharm 1(2):146–151

Chiteva R, Wairagu N (2013) Chemical and nutritional content of *Opuntia ficus-indica* (L.). Afr J Biotechnol 12(21):3309–3312

Chriyâa A (1998) Techniques culturales du cactus et de son utilisation dans l'alimentation des ovins en zones arides. Première journée nationale sur la culture du cactus au Maroc. El Kelâa des Sraghnas, pp 7–11

Costa RG, Beltrao Filho EM, Queiroga RCRE et al (2009) Partial replacement of soybean meal by urea on production and milk physicochemical composition in Saanen goats. Bras J Health Anim Prod 10(3):596–603

Costa RG, Trevino IH, De Medeiros GR et al (2013) Feeding behavior and performance of sheep fed cactus pear in substitution of corn. R Bras Zootec 42(11):785–791

Da Silva JA, Donato SLR, Donato PER et al (2016) Yield and vegetative growth of cactus pear at different spacings and under chemical fertilization. Rev Bras Eng Agric Ambient 20 (6):564–569

De Farias Ramos JP, Santos EM, Cruz GRB et al (2015) Effects of harvest management and manure levels on cactus pear productivity. Rev Cat Moss 28(2):135–142

De Waal HO, Schwalbach LMJ, Combrinck WJ et al (2013) Commercialization of sun-dried cactus pear (*Opuntia ficus-indica*) cladodes in feed-lot diets for Dorper Wether lambs. Acta Hortic 995:343–350

Dubeux JCB Jr (2016) Cactus: a crop for the dry areas. Broad Hori 28:1–4

Dubeux JCB Jr, Muir JP, Dos Santos FMV et al (2011) Improving grassland productivity in the face of economic, social, and environmental challenges. Rev Bras Zootec 40:280–290

Dubeux JCB Jr, Dos Santos MVF, De Mello ACL et al (2015) Forage potential of cacti on drylands. Acta Hortic 1067:181–186

El-Mostafa K, El Kharrassi Y, Badreddine A, Andreoletti P, Vamecq J, El Kebbaj MS, Latruffe N, Lizard G, Nasser B, Cherkaoui-Malki M (2014) Nopal Cactus (Opuntia ficus-indica) as a source of bioactive compounds for nutrition, health and disease. Molecules 19:14879–14901. https://doi.org/10.3390/molecules190914879

Emsley J (2011) Nature's building blocks: an A-Z guide to the elements, 2nd edn. Oxford University Press, Oxford

FAO (2013) Agro-industrial utilization of cactus pear. Rural Infrastructure and Agro Industrial Division. FAO, Rome

Farrukh H, Mufakhirah JD (2009) Seasonal availability, palatability and animal preferences of forage plants in Harbori range land, Pakistan. Pak J Bot 41(2):539–554

Felker P, Inglese P (2003) Short-term and long-term research needs for *Opuntia ficus-indica* (L.) Mill. utilization in arid areas. J Prof Assoc Cactus Dev 5:131–152

Felker P, Soulier C, Leguizamon G et al (2002) A comparison of the fruit parameters of 12 *Opuntia* clones grown in Argentina and the United States. J Arid Environ 52:361–370

Felker P, Casoliba RM, Filippini R et al (2005) Comparison of *Opuntia ficus-indica* varieties of Mexican and Argentine origin for fruit yield and quality in Argentina. J Arid Environ 60:405–422

Galati EM, Mondello MR, Giuffrida D et al (2003) Chemical characterization and biological effects of Sicilian *Opuntia ficus indica* (L.) Mill. fruit juice: antioxidant and antiulcerogenic activity. J Agric Food Chem 51(17):4903–4908

Gebreegziabher Z, Tsegay BA (2015) Efficacy of cactus pear (*Opuntia ficus-indica*) varieties as a source of food and feed in endamehoni district, Northern Ethiopia. Afr J Food Agric Nut Dev 15 (5):10406–10427

Gebremariam T, Melaku S, Yami A (2006) Effect of different levels of cactus (*Opuntia ficus-indica*) inclusion on feed intake, digestibility and body weight gain in tef (*Eragrostis tef*) straw-based feeding of sheep. Anim Feed Sci Technol 131(1–2):43–52

Godard MP, Ewing BA, Pischel I et al (2010) Acute blood glucose lowering effects and long-term safety of *Opuntia* supplementation in pre-diabetic males and females. J Ethnopharmacol 130 (3):631–634

Gonzalez CL (1989) Potential of fertilization to improve nutritive value of prickly pear cactus (*Opuntia lindheimeri* Engelm.). J Arid Environ 16:87–94

Griffith MP (2004) The origins of an important cactus crop, *Opuntia ficus-indica* (Cactaceae): new molecular evidence. Am J Bot 91(11):1915–1921

GRIN (2007) Opuntiaceae information from NPGS (National plant germplasm system) of GRIN (Germplasm resources information network). Taxonomic information on cultivated plants in the USA. National genetic resources program. United States Department of Agriculture, Agricultural research service. Maryland

Guevara-Arauza J, Paz J, Mendoza S et al (2013) Biofunctional activity of tortillas and bars enhanced with nopal. Preliminary assessment of functional effect after intake on the oxidative status in healthy volunteers. Chem Cent J 5:10–20

Gugliuzza G, Inglese P, Farina V (2002) Relationship between fruit thinning and irrigation on determining fruit quality of cactus pear (*Opuntia ficus-indica*) fruits. Acta Hortic 581:205–209

Hernández-Urbiola MI, Pérez-Torrero E, Rodríguez-García ME (2011) Chemical analysis of nutritional content of prickly pads (*Opuntia ficus-indica*) at varied ages in an organic harvest. Int J Environ Res Public Health 8:1287–1295

Inglese P (2010) Cactus pear *Opuntia ficus-indica* (L.) Mill. for fruit production: an overview. FAO Cactusnet Newsletter special issue

Kader AA (2002) Fruits in the global market. In: Knee M (ed) Fruit quality and its biological basis. Sheffield Academic, Sheffield

Kalegowda P, Haware DJ, Rajarathnam S, Shashirekha MN (2015) Minerals of cactus (*Opuntia dillenii*): Cladode and fruit. Curr Sci 109(12):2295–2298

Kuti O (2004) Antioxidant compounds from four *Opuntia* cactus pear fruit varieties. Food Chem 85 (4):527–533

Le Houerou HN (2002) Cacti (*Opuntia* spp.) as a fodder crop for marginal lands in Mediterranean basin. Acta Hortic 581:21–46

López-Romero P, Pichardo-Ontiveros E, Avila-Nava A et al (2014) The effect of nopal (*Opuntia ficus indica*) on postprandial blood glucose, incretins, and antioxidant activity in Mexican patients with type 2 diabetes after consumption of two different composition breakfasts. J Acad Nutr Diet 114(11):1811–1818

Mciteka H (2008) Fermentation characteristics and nutritional value of *Opuntia ficus-indica* var. *fusicaulis* cladode silage. M.Sc. thesis, University of the Free State. Bloemfontein, South Africa

Mengistu W (2001) Prickly pear cactus (*Opuntia ficus-indica*) as feed to ruminants. MSc Thesis. Swedish University of Agricultural Sciences, Uppsala, Sweden, 88p

Mondragon Jacobo C (2004) Mejoramiento genético del nopal: avances al 2003 y perspectivas. In: Esparza G, Valdez RD, Mendez S (eds) El nopal, topicos de actualidad. Universidad Automna de Chapingo, Mexico, pp 49–71
Mulas M, D'hallewin G (1997) Fruit quality of four cactus pear (*Opuntia ficus-indica* Mill.) cultivars as influenced by irrigation. Acta Hortic 438:115–122
Nefzaoui A, Ben Salem H (2000) Opuntiae: a strategic fooder and efficient tool to combat desertification in the WANA region. Cactusnet Newsletter special issue, pp 2–24
Nefzaoui A, Ben Salem H (2002) Forage, fodder, and animal nutrition. In: Nobel PS (ed) Cacti: biology and uses. University of California Press, Los Angeles, pp 199–210
Nobel PS (2002) Cacti: biology and uses. University of California Press, Los Angeles
Nobel PS, Bobich EG (2002) Environmental biology. In: Nobel PS (ed) Cacti: biology and uses. University of California Press, Los Angeles, pp 57–74
NRC (1976) Nutrient requirements of domestic animals. Nutrient requirements of beef cattle, 5th edn revised. National Research Council, Washington DC
NRC (1981) Nutrient requirements of domestic animals. Nutrient requirements of goats: Angora, dairy and meat goats in temperate and tropical countries, National Research Council. National Academy Press, Washington, DC
NRC (1985) Nutrient requirements of domestic animals. Nutrient requirements of sheep, 6th revised edn. National Research Council. National Academy Press, Washington, DC
Nuñez-López MA, Paredes-López O, Reynoso-Camacho R (2013) Functional and hypoglycemic properties of nopal cladodes (*O. ficus-indica*) at different maturity stages using in vitro and in vivo tests. J Agric Food Chem 61(46):10981–10986
Ochoa JM (2003) Cactus pear (*Opuntia* spp.) varieties main characteristics at Republica Argentina. Cactusnet Newsletter special issue, pp 3–29
Oliveira VS, Ferreira MA, Guim A et al (2007) Total replacement of corn and partial of tifton hay by forage cactus in diets for lactating dairy cows. Intake and digestibility. Rev Bras Zootec 36 (5):1419–1425
Piga A (2004) Cactus pear, a fruit of nutraceutical and functional importance. JPACD 6:9–22
Reis CMG, Gazarini LC, Fonesca TF et al (2016) Above-ground biomass estimation of *Opuntia ficus-indica* (L.) Mill. for forage crop in a Mediterranean environment by using non-destructive methods. Exp Agric 54:1–16
Rodrigues AM, Pitacas FI, Reis CMG et al (2016) Nutritional value of *Opuntia ficus-indica* cladodes from Portuguesse ecotypes. Bulg J Agric Sci 22:40–45
Rodriguez-Garcia ME, Lira C, Hernandez-Becerra E et al (2007) Physicochemical characterization of nopal pads (*Opuntia ficus indica*) and dry vacuum nopal powders as a function of the maturation. Plant Foods Hum Nutr 62:107–112
Saenz C (2004) Compuestos funcionales y alimentos derivados de *Opuntia* spp. In: Esparza G, Valdez R, Mendez S (eds) El Nopal, topicos de actualidad. Universidad Automna de Chapingo, Mexico, pp 211–222
Saenz C, Sepolveda E, Matsuhiro B (2004) *Opuntia* spp. mucilage's: a functional component with industrial perspectives. J Arid Environ 57(3):275–290
Sales AT, Andrade PA, Da Silva SD et al (2009) Adaptation potential of cactus pear to soil and climatic conditions of the Semi-Arid in Paraiba State, Brazil. Acta Hortic 811:395–400
Sangati CKR, Chenna Kesava RS, Sucharitha KV et al (2014) Medicated prickly pear (*Opuntia ficus indica*)-the new emerging agricultural crop in arid and semi arid regions of India. J Appl Biol Pharm Technol 5(4):264–270
Santo-Ares T, Venusa de Silva M, Alves de Almeido CM et al (2009) Genetic diversity in cactus clones using ISSR Markers. Acta Hortic 811:55–65
Shi H, Chen K, Ren S et al (2004) Development of *Opuntia dillenii* Haw beer. Food Sci Technol 2:79–81
Silva LM, Fagundes JL, Viegas PAA et al (2014) Cactus pear forage production under different plant densities. Ciencia Rural 44:2064–2071
Sloan E (2000) The top ten functional food trends. Food Technol 54(4):33–62

Stintzing FC, Carle R (2005) Cactus stems (*Opuntia* spp.): a review on their chemistry, technology, and uses. Mol Nutr Food Res 49:175–194

Stintzing FC, Schieber A, Carle R (2001) Phytochemical and nutritional significance of cactus pear. Eur Food Res Technol 212:396–407

Taddesse D, Melakub S, Mekasha Y (2014) Effect of supplementation of cactus and selected browses mix on feed utilization of Somali goats. Am Sci Res J Eng Technol Sci:2313–4402

Tafere G (2016) Cactus Pear, Cladodes (*Opuntia ficus-indica*); as forage for livestock in Arid and Semi-Arids of Ethiopia feeding under a changing climate – a review. J Integra Sci Inn Technol 5 (4):12–14

Tegegne F (2001) Nutritional value of *Opuntia ficus-indica* as a ruminant feed in Ethiopia. In: Mondragón Jacobo C, Pérez-Gonzalez S (eds) Cactus (*Opuntia* spp.) as forage. Cactusnet. FAO, Rome

Tegegne F (2002) Fodder potencial of *Opuntia ficus-indica*. Acta Hortic 581:343–345

Tegegne F, Kijora C, Peters KJ (2007) Study on the optimal level of cactus pear (*Opuntia ficus-indica*) supplementation to sheep and its contribution as source of water. Small Rum Res 72 (2–3):157–164

Tesoriere L, Allegra M, Butera D et al (2004) Absorption, excretion, and distribution of dietary antioxidant betalains in LDLs: potential health effects of betalains in humans. Am J Clinic Nut 80(4):941–945

UNDP/UNSO (1997) Aridity zones and dryland populations: an assessment of population levels in the world's drylands with particular reference to Africa. UNDP Office to Combat Desertification and Drought (UNSO), New York

Van Der Merwe LL, Wessels AB, Ferreira DI (1997) Supplementary irrigation for spineless cactus pear. Acta Hortic 438:77–82

Varela-Gamez Y, Caldera-Arellano AN, Jorge Zegbe A et al (2014) Irrigation in nopal influences the storage and packaging of tuna. Rev Mex Cienc Agri 5(8):1377–1390

Zegbe JA, Sánchez-Toledano BI, Serna-Pérez A et al (2014) Economic analysis of the application of mineral fertilizers on the yield of prickly pear. Rev Me de Ciencia Agric 5(3):449–461

Chapter 16
Replacement of Saffron (*Crocus sativus* L.) with Poppy (*Papaver somniferum* L.) and Its Socioeconomic Impact in Afghanistan

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Abstract Saffron (*Crocus sativus* L.) is a resilient crop with a high economic and culinary value. Currently, Afghanistan is the third largest saffron producer and exporter. However, the development of the industry is still in progress. Saffron has been cultivated regionally since 1998 by "the project on production and marketing of saffron" as a replacement for the cultivation of poppy. It is cultivated using a sustainable development and marketing approach and was supported by regional and local governments in Afghanistan, as well as several foreign NGOs. This book chapter highlights the outcome of a research project and its follow-up on saffron cultivation and production from a decade ago (2007/08) in Herat Province, Afghanistan. Since that time, saffron international price has fluctuated 5.3%. The product is easy to transport and store, and its cultivation, purchase, and export are legal. Additionally, based on farm prices, saffron has 4.5-fold higher revenue and can suitably replace poppy. Additionally, saffron cultivation provides seasonal jobs in two specific tasks: flower picking up and stigma flower separation. The tasks are undertaken entirely made by women and thus have a positive impact on female participation in the workforce. Finally, risks from saffron cultivation are minor in comparison with those of poppy, as saffron production is considered lawful and legal. For this reason, local religious leaders and authorities of Afghanistan support its cultivation and saffron farmers have superior social standings within their communities.

Keywords *Crocus sativus* · Afghanistan · Resilient crops · Gender participation

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16.1 Introduction

Saffron (*Crocus sativus* L.) is a high-value food product sold exclusively in grams and used in industrial, pharmaceutical, cosmetics, and textile purpose product in the world (Kafi et al. 2006a, b; Malik 2008). It is an ingredient for "biryani rice" and "paella" and for special sweets and pastries. According to Observatory of Economic Complexity (OEC) (2018) and to the Product Complexity Index (PCI), saffron is the 3442nd most traded product and the 4398th most complex product, due to its processing, packaging, and trading. Its worldwide trade is led by Iran, the largest saffron exporter (104M USD), followed by Spain (70.6M USD), Afghanistan (16.7M USD), France (8.03M USD), and Portugal (5.95M USD) (OEC 2018). The top worldwide importers in 2016 were Spain (53M USD), Italy (17.5M USD), the United Arab Emirates (16.8M USD), the United States (16.5M USD), and Argentina (15.3M USD). Besides, France, Algeria, Egypt, Germany, Australia, and China also have minimum saffron productions (Katawazy 2013). Afghanistan holds the position of the third largest producer and exporter of the spice. They primarily exported their saffron to a few key countries in 2016: India (84%), France (7.2%), Saudi Arabia (4.9%), the United States (1.4%), Bahrain (0.66%), and the United Arab Emirates (0.48%) (OEC 2018).

Saffron is cultivated as a cash crop in Afghanistan (Katawazy 2013; Wali et al. 2016). In 2016, 2811 ha of land in Afghanistan was used to cultivate saffron, a significant increase 1020 ha used for its cultivation 15 years prior (Fig. 16.1). This represents an increase 250% from previous levels (OEC 2018). This increase can be attributed to the crop's introduction and programmatic support by local and international institutions. Thus, the saffron cultivation and value chains have developed enormously in Afghanistan (OEC 2018).

Fig. 16.1 Local cultivation of poppy (*Papaver somniferum* L.) at farmer level

Several historical testimonies from c.a. two millennia ago mention that saffron was available in Afghanistan. Latterly, the records mention from 80 years ago some farmers restarted growing this saffron in Herat Province. In 1973, the Afghan Government implemented a saffron trial in Ordokhan Farm of Herat. After the return of refugees from Iran to Afghanistan in 1991, some who had been working in saffron fields in Iran brought back with them saffron corms, also named as "bulbs" or "onions," and on their return planted saffron in Ghorian District of Herat Province.

Due to the varied applications for saffron in food technology, medicine, drug, cosmetics, and its ecological adaptation in Afghanistan climate (2008), its cultivation has many advantages:

Box 16.1 Benefits of Cultivating Saffron in Afghanistan

- Creation of 270-day work per ha.
- About 80% of women's cooperation in saffron production and processing.
- Low water demand, simple cultivation, no mechanization necessity, and small farms.
- Simple transformation and storage.
- Profitability and exportability (Gohar and Wyeth 2006).
- Saffron generates more benefits than other crops.

Farmer's considerations for halal and legal cultivation.

Saffron cultivation was initiated by immigrants who came back from Iran to Afghanistan by conducting a research on "Investigation on production and marketing of saffron cultivation as substitution of poppy cultivation" on behalf of the International Center for Agricultural Research in the Dry Areas (ICARDA); Danish Committee for Aid to Afghan Refugees (DACAAR) a nonpolitical, non-governmental, non-profit humanitarian/development organization, which worked with farmers in Herat area with saffron since 1984; and the Ministry of Agriculture Irrigation and Livestock of Afghanistan (MAIL) in 1998; significant success has been achieved and saffron is increasingly been grown in Afghanistan (Katawazy 2013).

Nonetheless, the development of saffron production in Afghanistan has not met its potential. The country has been beleaguered by the cultivation of crops to produce illicit substances, like the farming of poppy to produce opium (*Papaver somniferum* L.). To combat this, in 2001, the Ministry of Narcotics in Afghanistan launched the National Alternative Livelihood Policy, which introduced the cultivation of high-value agricultural crops, like saffron, to the regions with large poppy industries (Ministry of Counter Narcotics, Afghanistan 2012; Wali et al. 2016).

Saffron is cultivated in more than 31 provinces, with Herat Province leading saffron cultivation nationally (TOLO 2016). Their saffron cultivation involves to around 6000 farmers. Saffron yields in 2016 were recorded at 4675 kg, with a total monetary value of 1.16M USD. The international saffron market demand increased every year, and in Afghanistan the saffron cultivation has increased since 2003

Fig. 16.2 Saffron (*Crocus sativus* L.) flower harvest entirely collected by hand and the women wearing gloves to avoid contamination

(Katawazy 2013). Due to its quality, Afghanistan saffron was named as the best in the world for the third time in 2018 by the International Taste and Quality Institute Brussels, Belgium (Fig. 16.2), where the Afghani variety stood out from the comparison of 300 samples conducted by them (ITQI 2018).

Saffron demand is increasing around the world, particularly within expatriate populations (OEC 2018). The saffron introduction, production, and trade involve many stakeholders. However, even with the growing demand and the aforementioned initiatives, poppy cultivation is still a continued challenge; the United Nations Office on Drugs and Crime (2017) reported that in 2016, opium poppy cultivation increased by 10% from the year before (from 183,000 to 201,000 ha). This estimate of poppy cultivation means 1500 t more of poppy was produced in 2016 than 2015.

This book chapter highlights a study carried out on saffron cultivation in the province of Herat in 2007 and 2008. Since that then, saffron cultivation initiatives have also been undertaken in other provinces. Data for this research was collected from farmers, who were trained in saffron cultivation in 29 provinces in 2007–2008 agricultural season. Further, it involved 37 saffron companies and 7 farmer associations. The project focused on the economic and socio-political impacts of replacing poppy with saffron.

16.2 Socioeconomic Importance of Saffron in Afghanistan

Saffron cultivation has a higher economic value than wheat, mung bean, bean, cabbage, and cotton (Gohar and Wyeth 2006). In terms of cultivated area, saffron is grown in 2811 ha of land in Afghanistan with 6000 kg of production (Fig. 16.3).

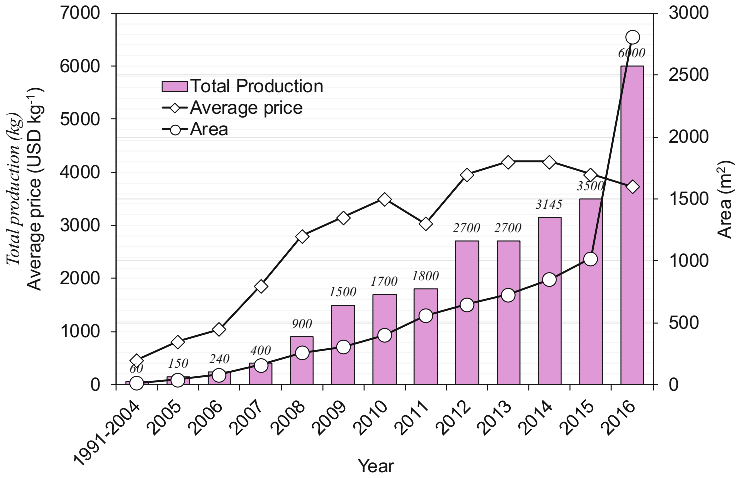

Fig. 16.3 Evolution of cultivated area, production, and price of saffron. Source: Saffron Development in Afghanistan 1991–2016

Table 16.1 Manual labour needed per year at conventional system (for 6 kg ha^{-1})

Planting stage (per person)	Man/day	Cropping practice (per person)	Man/day	Harvesting stage (per person)	Man/day
Manure distribution	10	Manure distribution	5	Flower harvesting	60
Field preparation	40	Irrigation	5	Styles cleaning	120
Corm gathering	100	Clot breaking	22	Drying	10
Corms cleaning	20	Weed control	20		
Corms planting	50	Foliage gathering	20		
Total	220[a]		75		190

[a]Average of 27 persons

Its 2007 and 2008 value is equivalent to 1400 to 1600 USD kg^{-1} and generates a total of 9M USD $year^{-1}$ from dry saffron spice and about 5M USD annually from selling saffron bulbs (MAIL 2016, OEC 2018). Studies over 3 years had mean yields per ha of 3.5 to 4 kg, with the highest yield recorded at 30 kg ha^{-1}. In general, 270 days of work is needed for each hectare of saffron; by these estimates 758,970 labour days are required for the cultivation of the estimated 2811 ha of saffron in 2016 (Malik 2008).

It is known that Afghanistan could potentially have 20,000 ha of saffron fields with a minimum of 70 t of production (Aslami 2008). In 2008, 29 provinces of Afghanistan were producing saffron. The cultivation generated 698,490 days of work, which is very important because women make up 80% of the workforce for saffron production and provide also provide jobs for farmers outside the main farming season (flower picking up at December) (Aslami 2008).

Fig. 16.4 Male farmer saffron producer association in Herat Province rural countryside

According to Table 16.1, 10% of the workforce is deployed during the planting stage, 25% during the cropping stage, and the majority, 65%, required during the harvesting stage. Its average foliage production is 800–1000 kg ha^{-1}, which can serve as nutritious animal feed for ruminants, as its nutrient content is higher than wheat straw and thus serves as a good option to support village economies. Estimate of farmer incomes from saffron corm in 2008 was 33,000 USD (produced corm per hectare during 5 years by price for 1 kg; 22,000 kg $\times$ 1.5 $=$ 33,000 USD). Land preparation, corm gathering, and planting are tasks conducted by men in the field. Crop management or the activities that keep the saffron plants clean do not require many labours. However, flower harvesting requires time-intensive labour and careful handling and is a task specifically conducted by women (Table 16.1). However, women often earn minimal incomes from these tasks, and many are forced move to other communities to harvest (Minoia and Pain 2016).

Income generation from saffron through corm production had a value of 1.5 USD kg^{-1} in 2008, and 20 to 22 t ha^{-1} was produced in 5-year-old saffron fields. Saffron cultivation provides jobs that prevent rural immigration for many members of the family, particularly women. Saffron has no interference with other crops, so it improves economic ability of farmers by using existing resources rationally. Its cultivation has positive effect on communication relations and increase social credit by doing legal and halal cultivation than poppy.

Production cost information of 1 hectare of saffron and poppy cultivation was collected from 5 saffron grower association and 20 producers in Herat (Fig. 16.4), for 2 successive years in 2007–2008. The data analysed considered the opinions as

Table 16.2 Cost estimation for cultivating 1 ha of saffron and poppy for 2007–2012

Saffron/Activity	Cost (USD)	Poppy/Activity	Cost (USD)
Land and water	2000	Land and water	2500
Corm	8000	Seed	40
Plough	27	Plough	150
Land preparation	28	Land preparation	250
Corm sowing	67	Seed planting	50
Fertilizer	980	Fertilizer	1150
Irrigation	365	Irrigation	500
Clot breaking	585	Clot breaking	0
Disinfection	10	Disinfection	150
Weed control	1825	Weed control	1500
Flower harvesting	3925	Cutting	4250
Corm gathering	500		
	18,312		10,540

Table 16.3 Sale estimation of saffron production in 5 years period in 2007 and 2008 based on world prices

Production type	Amount (kg)	Value (USD kg^{-1}) 2007	Value (USD kg^{-1}) 2008	Total value (USD) 2007	Total value (USD) 2008
Saffron	54.5	1200	1800	65,400	98,100
Corm	22,000	1.5	1.5	33,000	33,000
Forage	5000	0.03	0.03	150	150
				98,550[a]	131,250[b]

[a]Gross income
[b]Gross margin

well from native experts. Relative efficiency of saffron and poppy was determined for 5 years period in 1 hectare.

As resilient species, saffron cultivation needs a budget for the deployment in the field and the picking of flowers (Table 16.2). In contrast, poppy cultivation has higher costs for crop production, like land preparation, fertilization, and irrigation. However, saffron is an alternative crop, which does not need intensive labour for maintenance. Currently, saffron is a product in high demand for the use in food, pastry, and cosmetics. As saffron production continues, the corm and forage increase and it will positively affect on gross margin of farmers, as it will be a source of income for farmers and their families. The economic benefits from saffron production increase after the second year of production, as depicted in Table 16.3.

16.3 Economic Benefits of Saffron Cultivation

The cost of operating a 1-hectare saffron farm with the collected data in 2017 and 2018 was 10,362 USD, and its 5-year cost was equal to 18,312 USD (Table 16.2). Thus, the calculated gross margin according to price at worldwide level in 2007 was equal to 1200 USD kg^{-1}. Thus for 2007 the estimated value for 2007 was 98,550 USD (Table 16.3) and net profit for 5 years of 80,238 USD, or 16,048 USD annually.

Based on the 2008 world price of 1800 USD kg^{-1}, the gross margin was equal to 131,250 USD (Table 16.3), and net profit for 5 years was 112,938 USD which is 22,588 USD annually. Also, based on the 2008 local price, net profit for 5 years was 178,338 USD (35,668 USD annually). However, the cost of 1 hectare of poppy in 5 years period was equal to 10,540 USD (Table 16.2), and its net profit in 5 years period was determined 39,610 USD (7922 USD annually).

Thus, based on local price of saffron, saffron cultivation has 4.5 times more profit than poppy cultivation (Table 16.4). Saffron production is an alternative crop for poppy replacement. Also, risk of saffron cultivation against social threats is low, as its production is legal and halal (Katawazy 2013). Also, it is supported by the local religious scholars and the Afghanistan government. Thus, farmers that cultivate saffron have better social standing in their communities.

The production cost for 5 years estimated after 2007 and 2008 during the collection of information was 17,302 USD (Table 16.5). The cost for that moment were used for saffron seed purchasing (it is called seed the bulbs used to propagate the plants). The investment for land preparation and plant establishment does not require a big allocation of money. Nevertheless, seed in that time and until nowadays needs to be obtained with a high quality. Bulbs or corms of saffron are purchased from Iran, and the good quality will provide a good establishment of plants and good performance of saffron (described in Box 16.2).

Table 16.4 Sale estimation saffron and poppy production in 5-year period in 2008 since local prices

	Amount (kg)	Value (USD kg^{-1})	Total value (USD)
Saffron/production type			
Saffron	54.5	3000	163,500
Corm	22,000	1.5	33,000
Forage	5000	0.03	150
		Total	196,650
Poppy/production type			
Opium	250	200	50,000
Wood	–	–	150
		Total	50,150

Table 16.5 Estimated production cost for 1 ha of saffron planting (for a period of 5 years)

Activity	Quantity	Unit	Unit Cost (USD)	Amount (USD)
Land ploughing	16	Hour	10.6	169.7
Manure	30	Ton	27.3	818.2
Levelling	8	Hour	53.0	424.2
Land preparation	20	Person	3.8	75.8
Saffron seed	4000	Kg	3.8	15,151.5
Manual planting	175	Person	3.8	662.9
Subtotal (A)				17,302.27

Conversion rate for 1 USD = 66 AFN in 2008

Box 16.2 Saffron Cultivation Steps

Land Ploughing: This is done by tractor, usually plough 1 ha of land by two times in 16 hours.

Manure: Since only suitable organic fertilizer for saffron is cow manure, 30 t ha^{-1} was applied.

Levelling: This is done by a leveller connected to a tractor or a grader. The cost depends on distance of land from the city to the rural community and type of machine. This price is the average price in practice, and it may have more cost on this.

Land Preparation: Almost 20 people needed to prepare 1 ha of land for saffron planting. This task should be made after levelling otherwise the amount of labour for preparation would be higher.

Saffron Seed: This is the average cost; due to next year forecast and high level of demand of this plant, the average price will be higher than the current year.

Manual Planting: This is the minimum amount, and it has direct relation to the efficiency of the labour. So, we may need more.

The estimated annual cost for 5 years for cultivating saffron requires more investment for land, manure (usually consisted from animal to provide and sustain the soil adequately), and vigilance (patrol made by a person), a watchman is contracted for caring the plot. Another activity, which requires attention is weeding, and it is carried out by around three times (Box 16.3).

A big investment is needed for renting a land, when it will be required to produce more when the demand in the world market is increasing every year (Table 16.6). Manure, organic matter from animal source, is required, and the use and provision should have guarantee that it will provide every year with the same amount.

Table 16.6 Annual dynamic cost for 5 years of saffron cultivation

Activity	Quantity	Unit	Unit cost (USD)	No. of years	Total cost (USD)
Land rent	1	Ha	378.8	5	1893.9
Irrigation	1	Ha	121.2	5	606.1
Scratching	20	Person	3.8	5	378.8
Weeding	40	Person	3.8	5	757.6
Manure	10	Ton	27.3	5	1363.6
Watchman	2	Month	303.0	5	909.1
Land preparation	10	Person	3.8	5	189.4
Subtotal (B)				6098.48	

Conversion rate for 1 USD = 66 AFN in 2008

Box 16.3 Activities During 5 Years of Saffron Cultivation

Land Rent: This depends on the land gradation and distance from centre of city, the amount indicated above is calculated based on private lands. The government land is cheaper than this quantity, approximately 10,000–15,000 per hectare.

Irrigation: The estimated amount is based on solar irrigation system, which includes well construction and solar and pump installation. The considered solar system could cover 10 ha land.

Scratching: This task should be made before flower harvesting and after the second irrigation.

Weed: Weeding is required three times a year.

Fertilizer: Specific amount of natural and organic fertilizer is required to be added each year on land to increase harvest.

Watchman: One watchman is required for each 10 ha of land during the project.

Land Preparation: After planting, the land needs some preparation tasks, and labour task is needed to be included.

The saffron processing cost (Table 16.7) for 1 ha and estimated cost for 5 years comprised more investment for the payment in a sensitive task entirely made by women. Even in Iran or Spain and Afghanistan, the tasks of flower harvesting or picking up of flower and then the stigma separation need the attention and dedication (Box 16.4). Besides, the transporting of processed saffron demanded an investment when the processing centre was located far from the plot.

At the international market, saffron price is stable nowadays. Saffron cultivation and saffron flower picking and stigma separation provide job to women (Box 16.4). Saffron cultivation has been described as the crop flower product for women, during flowering and after flower processing.

Table 16.7 Saffron processing cost for 1 ha in 5 years

Activity	Quantity	Units	Unit price (USD)	No. of years	Cost (USD)
Flower harvesting	540	Kg	0.5	5	1227.3
Flower transportation to process centres	540	Kg	0.0	5	122.7
Stigma separation	540	Kg	0.9	5	2454.5
Stigma transportation to drying centres	31.32	Kg	0.3	5	47.5
Drying	6	Kg	7.6	5	227.3
Physical cleaning	6	Kg	3.8	5	113.6
Processing centre rent	2	Month	54.5	5	545.5
Admin cost	2	Month	51.5	5	515.2
Accommodation cost	2	Month	45.9	5	459.1
Technical staff salary	2	Person	68.2	5	681.8
Transportation cost	2	Month	136.4	5	1363.6
Drying machinery cost	2	Set	272.7	5	545.5
Packaging	6	Kg	1.5	5	45.5
Subtotal (C)					8348.96

Conversion rate for 1 USD = 66 AFN in 2008

Box 16.4 Saffron Flower Postharvesting Activities

Flower Harvesting: Total harvesting cost of flowers from 1 ha in a 5-year period estimated to be 2700 kg, which approximately produced 30 kg dried saffron.

Stigma Separation: Each kg of flower produces 50–60 g of wet stigma.

Drying: The indicated cost was for electricity consumption and wage for a person who was responsible for drying. An amount of dried saffron produced from 1 ha land would be 6 kg in a period of 5 years.

Processing Centre Rent: The estimated amount of saffron to be processed in one processing centre was 100 kg, and the salary of one person was 15,000 AFN/month (227.3 USD/month), and the indicated amount was calculated for 1 ha production.

Admin Cost: This amount included costs for one computer, one printer, and all stationery required for a period of 5 years.

Accommodation cost: This amount included office electricity consumption and accommodation for staff for a period of 5 years.

(continued)

Box 16.4 (continued)

Technical staff Salary: Since one processing centre is assumed to process 100 kg, indicated amount was calculated relatively for 30 kg saffron.

Transportation cost: One car was required for one process centre, and the approximate rent for one car was 30,000 AFN (454.5 USD) with the driver, so indicated amount was calculated relatively to 30 kg saffron.

The total cost for cultivation and production of saffron based on prices and cost collected in 2007 and 2008 was 31,749 USD for 5 years (Table 16.8). The land and the climate in Afghanistan, in Herat Province, are appropriate for saffron. The cost for the implementation, which consists in saffron planting requires high investment, the saffron flower processing, and the maintenance of the crop (previously described in Boxes 16.2 and 16.3).

The production of saffron stigma and corm provide a return of 119,580 USD for 5 years. Now, three main countries are leading the saffron stigma production, Iran, India, and Afghanistan. Afghanistan has taken important rule, due to shifting from poppy cultivation as an illegal crop to cultivation of saffron with many advantages such as social, ecological, economical and gender equity (Table 16.9).

The cultivation of saffron for 1 ha and estimated for 5 years provides a total benefit of 87,830 USD after producing 30 kg ha^{-1}. Price at international level of saffron would depend on the demand. Nevertheless, since this research was carried out, based on the price of 2008, solely a 5.3% of variation had since that year (c.a. 10 years ago). Afghanistan has a strong potential to keep as the third supplier of saffron due to the impact for the rural households.

16.4 Conclusions

As a versatile crop species, saffron is a low nutrient demand plant and requires modest amounts of nutrients. Currently, it is highly demanded cooking product in the Middle East countries and is a delicacy in many regional cuisines. The most

Table 16.8 Total expenses for a duration of 5 years

Description	Cost (USD)
Estimation for saffron planting (1 ha) (A)	17,302.27
Annual dynamic (B)	6098.48
Saffron processing (from 1 ha) (C)	8348.96
Total expenses (TE)	31,749.72

Rate exchange: 1 USD = 66 AFN

Table 16.9 Total return from 1 ha after 5 years

Description	Quantity	Units	Unit price (USD)	No. of year	Amount (USD)
Saffron stigma production	30	Kg	1970	5	59,100
Saffron seed production	16,000	Kg	3.78	5	60,480
Return amount (RA)				119,580	

Therefore, Total Benefit for 1 hectare after 5 years is as follows: *Total Benefit (TB) = RA – TE; TB = 119,580–31,749 = 87,830 USD*

renown producer of the plant is Iran; nevertheless, Afghanistan appears as another saffron provider, and its cultivation serves as a viable alternative to poppy cultivation. Poppy cultivation is forbidden, and some of its by-products are extremely harmful for human health. Additionally, the growth of poppy demands more investment in land preparation, husbandry, and irrigation. In contrast, saffron only requires labour for its planting and flower harvests. Socially, it is massively impactful on gender; women can be involved in every stage of the harvesting, postharvesting, and processing of flowers for its commercial purposes. The economic benefits of saffron cultivation for the first and second year is low, however, after the third harvesting cycles, the benefits are clearer and show signs of increasing. Above all, the cultivation of saffron is ecologically sound and its impact on nutrient soil fertility is beneficial.

This chapter highlights the impact of an implemented project on saffron introduction and as an alternative for replacing poppy. As resilient crop and part of the culture of Afghanistan and its neighbouring countries, saffron is very demanded and highly cost product in Middle East countries, specifically in the United Arab Emirates, besides in many parts of the world where expatriates from India, Pakistan, and Afghanistan are living and use it for the preparation of "biryani" and above all from Spain for cooking "paella rice." The current use of saffron stigma flower is in cooking, albeit its use includes the cosmetics and pharmaceutics.

Poppy cultivation is a threat for saffron sustainability. Saffron production provides jobs for both men and women. In terms of natural resource management, this crop does not demand extra labour. In social and in gender aspect, women are benefited for getting access to the job and their dedication in the specific task on saffron flower picking up and stigma flower processing.

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References

Aslami MH (2008) Saffron cultivated area production, price, and export situation in world. Presentation on the third Afghan national conference of saffron in Herat province. 12 and 13 of November 2008

Gohar A, Wyeth P (2006) Saffron production and farmer perceptions in Pashtun Zarghun district of Heart. Short Report by DACAAR Field Staff, May 2006 – November 2006. Research in Alternative Livelihoods Fund, RALF. 13p. https://assets.publishing.service.gov.uk/media/57a08c4ce5274a27b20010ef/RALFSaffron_prodn_in_Herat-AG-PW-Nov06.pdf

International Test and Quality Institute (2018) Awarded products 2016. International Test and Quality Institute, ITQI. Brussels. https://www.itqi.com/en/awarded-products/awarded-products-2016/

Iran Daily (2018) Iran's saffron exports hit 10 year-high. Consulted 28 October 2018. http://www.iran-daily.com/News/216587.html

Kafi M, Kakhki AH, Karbasi A (2006a) Chapter one: Historical background, economy, acreage, production, yield and uses. In: Kafi M, Koocheki A, Rashed MH, Nassiri M (eds) Saffron (*Crocus sativus*). CRC Press, Taylor & Francis Group, pp 10–20

Kafi M, Koocheki A, Rashed MH, Nassiri M (2006b) Saffron (*Crocus sativus*): production and processing. CRC Press, Taylor & Francis Group, 252p

Katawazy AS (2013) A comprehensive study of Afghan saffron. Afghanistan Investment Support Agency, AISA. Research, Planning and Policy Directorate, April 2013. Kabul, Afghanistan, 46p. https://www.doc-developpement-durable.org/file/Culture-epices/safran/Commercial/A%20comprehensive%20study%20of%20afghan%20saffron.pdf

Malik N (2008) Saffron manual for Afghanistan: planting, maintenance, harvesting and processing. DACAAR, ICARDA, DFID. Kabul, Afghanistan, 34p

Ministry of Agriculture, Irrigation and Livestock of Afghanistan (2016). Agricultural commodities price monitoring online database. Ministry of Agriculture Irrigation and Livestock of Afghanistan, MAIL. (Cited 2018 October, 12). http://mis.mail.gov.af/pis/

Ministry of Counter Narcotics, Afghanistan (2012) National Alternative livelihood policy. Kabul, Afghanistan (internet), (cited 2018 October 21). http://mcn.gov.af/Content/files/AL_En.pdf

Minoia G, Pain A (2016) Saffron: the social relations of production. Researching livelihoods and services affected by conflict. Working paper 48. Secure Livelihoods Research Consortium, SLRC. London, 40p. https://assets.publishing.service.gov.uk/media/5901ed3eed915d06b0000216/WP48_Saffron_The_social_relations_of_production.pdf

Observatory of Economic Complexity (2018) Saffron: import, export and trade trends. Observatory of Economic Complexity, OEC. https://atlas.media.mit.edu/en/resources/about/

TOLO (2016) Saffron cultivation hits record high in Afghanistan. Business. TOLO news. Accessed 18 Oct 2018. https://www.tolonews.com/business/saffron-cultivation-hits-record-high-afghanistan

United Nations Office on Drugs and Crime (2017) Sustainable development in an opium production environment. Afghanistan Opium Survey Report 2016. United Nations Office on Drugs and Crime, UNODC. Islamic Republic of Afghanistan, Ministry of Counter Narcotics. Kabul, 87p. https://www.unodc.org/documents/crop-monitoring/Afghanistan/Afghanistan_sustainable_development_for_web.pdf

Wali E, Datta A, Shrestha RP, Shrestha S (2016) Development of a land suitability model for saffron (*Crocus sativus* L.) cultivation in Khost province of Afghanistan using GIS and AHP techniques. Arch Agron Soil Sci 62(7):921–934. https://doi.org/10.1080/03650340.2015.1101519

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