Indian J. Genet., 74(4) Suppl., 553-557 (2014)
DOI: 10.5958/0975-6906.2014.00888.8

Genetic enhancement of food legumes for nutritional security and sustainable cereal-based cropping systems

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(Received : October 2014; Revised : November 2014; Accepted : November 2014)

Abstract

Food legume crops are cultivated since the earliest days of agriculture for human food and animal feed. Today these crops are grown globally, providing food and nutritional security. In particular, they are the main source of protein, macro and micronutrients in the diets of medium to low-income people in most developing countries. Besides their nutritional value, food legumes are important nitrogen fixers, contributing to soil health improvement and thus providing sustainable cropping system. However, global food legume production of about 67 million tons per year is insufficient to meet demand from ever-increasing populations, particularly in Africa and Asia. Food legumes are grown mainly by small and marginal farmers under rainfed conditions in marginal areas, leading to low and unstable yields. Moreover, they have long been 'orphan crops', receiving very little attention from researchers and policy makers. To attain a sustainable increased production in food legumes, several international research centers are working closely with national institutions to address these issues. The International Center for Agricultural Research in the Dry Areas (ICARDA), located in the center of origin of many food legume species, is engaged in research to develop and deliver improved food legume technologies to farmers. The research covers multiple crops (lentil, faba bean, Kabuli chickpea, grasspea) and involves a multidisciplinary team comprising breeders, biotechnologists, pathologists, entomologists, and seed specialists, To date, a total of 368 improved varieties of these crops have been released for cultivation in various countries, jointly developed by ICARDA and national partners.

Key words: Food legumes, rainfed areas, genetic diversity, micronutrients, diseases

Introduction

Food legumes play a significant role in the more efficient use of land and water resources and diversification of crop production systems. Because of their ability to fix atmospheric nitrogen, food legume crops, when used in crop rotations, improve soil fertility and health, diversify the cropping systems and ensure the sustainability of agricultural production systems. They also contribute to food and nutritional security, income growth, poverty alleviation and employment generation through agro-industries. Food legumes are a vital source of protein, especially for the poor, who often cannot afford animal products. Food legumes contain high amounts of protein, macro- and micronutrients (Ca, P, K, Fe, Zn), vitamins (niacin, Vitamin A, Ascorbic Acid, Inositol), fiber and carbohydrates for balanced nutrition [1] . They are rich in lysine, an essential amino acid which is found only at low levels in cereal protein. They also complement cereals in terms of nutrition, e.g. cereals are high in sulphur-containing essential amino acids such as methionine, cystine and tryptophan. Thus, cereal-legume food systems contribute to balanced nutrition and provide nutritional security to low-income people in the developing countries. In addition to their role in human nutrition, they are valuable sources of animal feed and an integral part of crop-livestock systems in the developing world, particularly in South, West and Central Asia, and North and East Africa.

Through concerted efforts by national and international institutions, total production and productivity of pulses have increased during the past decades. Progress has been made to resolve agronomic issues, improve weed control, develop screening techniques, identify resistance to key biotic and abiotic stresses, and develop improved varieties and production technologies [2]. Nevertheless, a quantum jump in productivity has not been achieved,

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Published by the Indian Society of Genetics & Plant Breeding, F2, First Floor, NASC Complex, PB#11312, IARI, New Delhi 110012
Online management by indianjournals.com

unlike the case with cereal crops like wheat and rice during the Green Revolution. There is a substantial yield gap between research plots and farmers' fields. There is great potential for increasing production and yields of food legumes, but these crops usually receive minimal inputs compared to cereals, creating a major issue in terms of the yield barrier. The future potential of food legumes may be in the more favored areas, from where these crops have been displaced, and where mono-cropping of cereals is no longer sustainable. A multidisciplinary research effort is underway to address various key issues-yield improvement, enhanced stress resistance, quality traits and improved production practices.

Among grain legumes, International Center for Agricultural Research in the Dry Areas (ICARDA) has a research mandate on lentil, faba bean, Kabuli chickpea, and grasspea which are an integral part of subsistence rain-fed farming systems. Together, these crops occupy 22 m ha area with 22.5 million tons production and ~1000 kg/ha average productivity at global level. Past research and development efforts at ICARDA have resulted in development of improved varieties with resistance to key diseases such as *Fusarium* wilt and *Ascochyta* blight in chickpea, *Fusarium* wilt, rust, and *Ascochyta* blight in lentil, and *Ascochyta* blight, and chocolate spot in faba bean in addition to production technologies [3] . The most significant improvement in yield stability has resulted from the genetic recombination in these crops to develop appropriate phenology so that the durations of the vegetative and reproductive periods are well matched with photoperiod, temperature and expected soil moisture. This has been possible because of the active collaboration between ICARDA and NARS partners of over 40 countries on legumes research and development.

ICARDA holds one of the largest collections of food legume germplasm (12,454 lentil, 9,993 faba bean, 14,899 chickpea, and 4,165 grasspea) comprising wild and cultivated species. These resources are key building blocks for genetic enhancement in these crops. Except for a few traits, sufficient variability for important economic characters including stress resistance is present in these germplasm. The germplasm and breeding lines developed at ICARDA are shared on regular basis with national partners in the form of various international and special nurseries. To increase the use of germplasm in breeding programs, the Focused Identification of Germplasm Strategy (FIGS) is being used at ICARDA with robust geographical data sets. The strategy has proven successful for various adaptive traits such as tolerance to heat, drought, cold, and salt, besides resistance to insect pests and diseases. Such FIGS sets in chickpea, lentil and faba bean are now available to NARS partners to discover and deploy the useful genes into desired agronomic background.

The breeding objectives at ICARDA and in national programs are targeted to address the specific needs of different agro-ecological regions. Following a selection-hybridization-selection cycle, ICARDA constructs new genotypes of these crops to deliver to the national programs. ICARDA supplies nurseries to national programs comprising a range of genetically fixed materials and segregating populations to select according to their specific needs. On the basis of phenological adaptation, agronomically desirable traits, resistance to prevailing stresses, quality aspects, farmer's and consumer's preference, etc., national scientists identify and select promising lines/single plants for eventual release for commercial cultivation. A total of 368 varieties of lentil (137), faba bean (62), *kabuli* chickpea (162) and grasspea (7) have been released for cultivation in various countries, and are adopted by farmers. Some of the success stories of ICARDA partnership with NARS are well documented.

Adoption of improved production technologies and new varieties has generated substantial impact at farm level. One of the major achievements in lentil is the breaking of an ancient bottleneck of narrow genetic base in South Asia, which produces nearly 40% of world's lentil. Genetic base has been broadened through introgression of genes from ICARDA germplasm in the region involving primitive land races and wild relatives. Collaborative efforts between ICARDA and Bangladesh national programs have resulted in development of improved varieties like BARImasur-4, BARImasur-5, BARImasur-6 BARImasur-7 and BINAmasur-7 which has helped in improving lentil productivity in the country. An impact study showed that these improved varieties are cultivated over 110,000 ha in Bangladesh, delivering an annual extra production gain of some 55,000 tons, and valued at US$ 38 million annually. An IFPRI impact study in showed that the release and uptake of high yielding, rust and wilt resistant lentil varieties in Ethiopia has increased the growing area and harvest at an annual rate of 15% from 1994 to 2009. This resulted in 105,956 ha cropped area with lentils, and 123,777 tons of production in the country.. Besides, Shekhar, Sital, Khajurah-, Khajurah-2, Sagun, Simal, MP Bharati in Nepal; dlib-2, Idlib-3 and Idlib-4 in Syria; Bakria, Hamria, Bechatte in Morocco; Arzu in Azerbaijan; Pablo in Georgia and Darmon and Altindon in Uzbekistan are cultivated by farmers.

Winter chickpea technology with appropriate varieties and matching production technologies has been developed and adopted by farmers in several countries of Central Asia, North Africa and West Asia regions, significantly increasing productivity compared to traditional spring-grown chickpea. The popular winter-sown chickpea varieties include Ghab-3, 4, and 5 in Syria; FLIP 84-92C in Algeria and Tunisia; Yialousa in Cyprus; IPA 510 in Iraq; Baleela-2 in Lebanon, Zahor in Morocco; Elvar in Portugal; and Sari-98 and Gokce in Turkey; Elixir in Georgia; ICARDA-1 in Kazakhstan; Rafat in Kyrgyzstan; Narmin in Azerbaijan),. The drought-tolerant chickpea variety Gokce, developed at ICARDA and released in Turkey for early spring sowing, is now grown on over 350,000 hectares.

Multiple disease-resistant faba bean varieties in Ethiopia, China, Morocco and Egypt have substantially increased productivity and production. One major impediment to faba bean cultivation in the WANA region is the parasitic weed, Orobanche. Appropriate IPM packages and tolerant/resistant varieties have been developed and adopted by farmers in several countries. In grasspea, cultivation of the low-toxin variety Waise in Ethiopia and BARIKhesari-3 in Bangladesh are good example of successful collaboration.

Quality improvement in food legumes is another important issue, and involves two aspects: enhancing beneficial nutrients and reducing anti-nutritional elements. Nutrition can be enhanced in various ways (food diversification, supplementation, food-product fortification and biofortification). The best option could be biofortification, where concentration of nutrient elements in seeds is increased through plant breeding. According to a UN report, deficiency of various essential elements (iron, Zinc and Vitamin A) is alarming in Africa and Asia, and women and children are the worst sufferers. High iron and zinc lentil varieties have been released in Nepal, Ethiopia, Syria, Turkey, Portugal, and Bangladesh [4]. However, research on quality improvement needs to be strengthened and expanded to other major food legumes. One important opportunity relates to ß-ODAP, a toxic substance present in grasspea seed, which causes neurolathyrism, an irreversible paralytic syndrome if consumed in excess. High ß-ODAP varieties are grown and eaten in Bangladesh, Ethiopia, India, Nepal, Pakistan and parts of China because the poor face “the choice between starvation and accepting serious health risks”. As ß-ODAP synthesis in seeds/plants is genetically controlled, efforts are underway for genetic detoxification to make grasspea safe its consumption.

Food legumes are grown in various cropping systems as sole crops, mixed and intercrops. However, there is great scope for expansion in new cropping systems niches. For example, Turkish farmers successfully adopted chickpea and lentil in wheat fallows. Similarly, rice fallows in India, Nepal and Bangladesh can be utilized by introducing appropriate varieties of lentil, grasspea and chickpea. In Bangladesh, a new pattern, monsoon rice-lentil/ chickpea-spring rice can replace rice-rice systems. The development and adoption of extra-early maturing (<100 days) varieties is the best way to achieve this. Appropriate lentil, chickpea and grasspea cultivars adapted to relay cropping (broadcast in standing rice crop) with fast germination and early root penetration with long tap root traits is another area where research is warranted.

The current research programs of lentil, faba bean and kabuli chickpea at ICARDA have been aligned with CGIAR Research Program (CRP) on Grain Legumes to address either persistent challenges to their production or strive to advance unrealized potentials and opportunities. Built on the past successes, germplasm collections, and recent progresses in science, research efforts are directed involving both conventional breeding approaches and modern molecular tools to develop the following product lines:

Climate-smart varieties

Predicted climate change brings many challenges to plant breeders. In the past it may have been sufficient to develop a variety well adapted to a particular agro-ecological region taking into account the well understood abiotic and biotic constraints and end-product quality. With climate change becoming a reality, breeders have to consider, in addition, how the variety will perform in an environment with higher concentration of CO_2 and larger variability in temperature and water availability. Understanding each of these constraints will facilitate breeders to design appropriate adaptation strategy to changing climates. Drought stress, especially after the onset of flowering, is of common occurrence in most of the environments, causing substantial yield losses. We work to improve and stabilize the yield potential of these crops by incorporating genes for drought tolerance, productivity and key diseases. Drought research at ICARDA is conducted across various moisture gradients to capture the expression of genotypes under low, medium and high moisture conditions. The current methodologies are in use to screen a large number of lines for drought include delayed planting of germplasm/

improved materials to coincide the critical growth stage with high moisture stress. Additionally, the conventional methodologies are being supplemented with better and automated phenotyping facilities and molecular tools to understand the complex nature of drought tolerance. Similarly, heat stress during the reproductive phase adversely affects pollen viability, fertilization, pod set and seed development leading to abscission of flowers and pods, and substantial losses in grain yield. Pollen-based screening methods have been useful for evaluating genotypes for tolerance to heat stress both in lentil and chickpea. We also evaluate our germplasm of faba bean, chickpea and lentil in Sudan, where the crops experience heat stress throughout its reproductive phase. Genetic variation for heat tolerance has been identified in these crops. The precision and efficiency of breeding programs for climate smart varieties have been enhanced by integrating novel approaches, such as high throughput phenotyping, rapid generation turnover, marker-assisted selection, and genome wide selection. Efforts are underway to mainstream these tools into routine breeding programs.

Managing biotic stresses

The combined effect of insect pests, diseases and weed infestations on grain legumes causes an estimated 37-70% of total yield losses. Improved production performance require basic resistance to major diseases, including Botrytis gray mold, *Ascochyta* blight, collar rot and *Fusarium* wilt in chickpea; *Stemphylium* blight, collar rot, rust, and *Fusarium* wilt in lentil [5] ; and chocolate spot, rust, Ascochyta blight, black root rot, stem rots, root rots/damping-off, bean yellow mosaic virus, bean true mosaic virus, bean leaf roll virus and bean yellow necrotic virus in faba bean. A great progress has been made in solving individual diseases and now the efforts are underway for multiple disease resistance. Since the value of resistance sources depends upon levels and stability of their resistance, a complete understanding of resistance-associated factors for critical traits in the available germplasm has the potential to bring them together in a selection index, and ultimately use them in pyramiding using molecular tools in breeding programs.

Chickpea is devastated by insect pests, particularly the pod borers and leaf miner, and lentil and faba bean by aphids. The levels of resistance to pod borers in the cultivated germplasm are quite low, and hence, there has been little progress in developing cultivars with adequate levels of resistance to the target pests in these crops. However, wild relatives do have high levels of resistance to these pests. Good sources of resistance against pod borers and leaf miner in chickpea and Sitona weevil in lentil have been identified in the wild germplasm for use in the breeding program. Under the CRP, we are striving to develop Insect-smart production systems' through an Integrated Pest Management (IPM) approach that integrate the application of genetic engineering and genomic tools, wide hybridization, and rational application of biopesticides and synthetic pesticides to guide decision-making in pest management. The integration of transgenic plants with high levels of resistance to pod borers and management approaches will act as a major game changer to provide a sustainable solution to these intractable pest problems. For biological control, our approach is 'discovery-to-deployment' pipeline involving identification of better-adapted natural enemies against this pest, and efficient system for rearing of the natural enemies.

Extra-early varieties

South Asia's farming systems are dominated by two cereal systems: rice-wheat (9.77 m ha) and rice-rice (2.12 m ha) systems. In the Indo-Gangetic Plain (IGP), expansion of more productive wheat in northern India and boro-rice in eastern India and Bangladesh has resulted in substantial reductions of chickpea and lentil cultivation. With cereal yields projected to double over the next 30 years, legumes are likely to be pushed out, unless extra-early varieties of cool-season food legumes especially chickpea, and lentil are developed that can fit in these cropping systems [6] . Extra-early varieties (<90 days) escape end-of-season drought and heat stresses in addition to fitting the crops in available short windows of these cropping systems. In addition, increased adaptability to marginal soil conditions and matching water availability during the critical growth stages will also be required. The extra-early *kabuli* chickpea variety ICCV2 expanded the production of *kabuli* chickpea in the tropical environments and is a leading variety in Myanmar and KAK2 and JGK1 in India. A similar success can be achieved in the eastern IGP with the deployment of appropriate extra-early varieties of lentil and chickpea with resistance to key diseases and pod borers of the region and with appropriate ICM technologies.

Herbicide-tolerant varieties

Weeds (parasitic and non-parasitic) continue to be a major production constraint to grain legumes production. Non-parasitic weeds compete with crops for light and nutrients, often leading to significant yield losses of up to 40% in legume crops. Manual weeding has become uneconomical and impractical for many smallholder farmers due to competing on- and off-farm activities and high labor wages. Although specialized post-emergence herbicides are available, they often have unsatisfactory effects on legumes due to serious phytotoxic effects. While existing selective herbicides do not harm the crop, they are not very effective in eliminating some important types of weeds. Use of non-selective herbicides is effective in removing all types of weeds in a single application; however, herbicide resistant varieties need to be developed. Non-transgenic approaches, either by exploiting the existing genetic variability within the germplasm or by inducing novel mutations, have shown promise for development of herbicide-tolerant varieties in the recent past. For example, varieties with improved tolerance to herbicide metribuzin were developed by screening the advanced breeding lines for herbicide tolerance in lentil and chickpea. Genotypic differences have been reported for tolerance to imidazolinone class of herbicides in chickpea, lentil and faba bean. Commercial herbicide-tolerant crops developed from herbicide-tolerant mutants include imidazolinone-tolerant lentil.

Besides common weeds, parasitic weeds like *Orobanche* have also emerged as a major threat especially to faba bean and lentil production in West Asia and North Africa region and East Africa, leading to substantial reduction in area and production [7] . Genetic tolerance has been discovered in these crops to manage parasitic weeds. Integrated broomrape management practices that also include herbicide-tolerant faba bean cultivars have been developed by ICARDA for WANA region. Thus, exploiting the genetic variability, both existing and induced, can be a potential approach to develop herbicide and parasitic weed tolerant legume varieties.

Machine harvestable varieties

Manual harvest of legume crops is becoming increasingly uneconomical because of the rising labor cost and shortage of labor at the peak harvest time. In order to use combine-harvesters, legumes varieties need to be modified for machine harvestability. This requires development of varieties with erect and tall plants, strong stems, top pod bearing habits, synchronous maturity; and tolerance to lodging and pod shattering [8]. Genetic variability for these traits exists in the germplasm. The utilization of available genetic variability for plant traits in breeding programs have augmented breeding programs in the development of improved breeding lines suitable for mechanical harvest. Mutants with upright growth habit have also been identified and used for development of improved breeding lines in chickpea and lentil. A large number of breeding lines with upright growth habit and suitable for mechanical harvesting is under field testing and would soon be available for cultivation.

In conclusion, there is a need to employ a more integrated approach to use the existing genetic and genomics resources for uplifting the current yield level in lentil, faba bean and chickpea. The application of molecular approaches for legumes improvement is expected to be the part of mainstream breeding programs in the international and national programs which will contribute immensely for developing improved cultivars with higher yield and stability. This will provide further opportunities to ICARDA to collaborate with national programs for improving rural livelihoods, nutritional security and providing sustainable cereal-based production systems.

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