Hari Deo Upadhyaya: Plant Breeder, Geneticist and Genetic Resources Specialist

Sangam L Dwivedi
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Telangana, India

ABSTRACT

This chapter discusses Hari Deo Upadhyaya, a plant breeder, geneticist and genetic resources specialist, and his contributions in management and utilization of genetic resources, molecular biology and biometrics, and in groundnut breeding. Hari's contributions in genetic resources include enriching germplasm collections; forming representative subsets in the form of core and/or mini-core collections in chickpea, groundnut, pigeonpea, pearl millet, sorghum, and six small millets; unlocking population structures, diversity and association genetics; and identifying genetically diverse and agronomically desirable germplasm accessions for use in crop breeding. The Consultative Group on International Agriculture Research (CGIAR) recognized his concept and process of forming mini-core collection as International Public Goods (IPGs) and researchers worldwide are now using mini core-collections as useful genetic resources in breeding and genomics of the aforementioned crops. A genebank manager's role isn't just confined to collection, maintenance, and archiving germplasm. Hari's spirited efforts prove so and they led many to realize the abundant opportunities to mine and enhance the value of the genetic resources in crop improvement programs. As a geneticist, his seminal work on wilt resistance in chickpea laid a strong foundation for the wilt resistance breeding programs globally. His contributions as a groundnut breeder resulted in the release of 27 cultivars in 18 countries, some widely grown, and 24 elite germplasm releases with unique characteristics made available to groundnut researchers

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worldwide. Hari's inimitable ability and scientific competence allowed him to collaborate with diverse groups and institutions worldwide. His scientific contributions in germplasm research and groundnut breeding have been recognized with several prestigious global awards and honors. A prolific writer and with immense passion for teaching, Hari Upadhyaya has established a school of his own for the management, evaluation and use of genetic resources for crop improvement.

KEYWORDS: Breeding, Climate resilient germplasm, core and mini-core collections, crop wild relatives, cultivars, elite germplasm, farmers participatory variety selection, molecular breeding, population structure and diversity, on-farm conservation of germplasm

OUTLINE

ABBREVIATIONS

ASA	American Society of Agronomy
CGIARC	Consultative Group on International Agricultural Research Consortium
CSSA	Crop Science Society of America
ICRISAT	International Crops Research Institute for Semi-Arid Tropics
NARS	National Agricultural Research Systems
R4D	Research for development
SNP	Single nucleotide polymorphisms

I. INTRODUCTION

Hari Deo Upadhyaya, whom many of us know as Hari, has been known to me since 1980, when he joined the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, as a postdoctoral fellow in chickpea breeding. After completing his post-doctoral assignment at ICRISAT, Hari then moved for a short period to work as the Pool Officer at 'GB Pant' University of Agriculture and Technology (GBPUAT), Pantnagar, India, the first agricultural university established on a US 'Land Grant' pattern in India. He then took up a regular position at the University of Agriculture Sciences (UAS), Dharwad, India, where he worked for almost for eight years, first as a soybean breeder (as Assistant Professor), and then as the head of the oilseeds scheme and a groundnut breeder (as Associate Professor). He did a remarkable job as an oilseed breeder, and he set up and took the soybean and groundnut breeding programs to newer heights.

In 1991, Hari returned to ICRISAT as a Senior Groundnut Breeder. In late 1997, ICRISAT reorganized its research portfolio, and moved Hari on a part-time basis to the Genetic Resources Unit, as part of the Crop Improvement Program. In 2002, Hari was appointed as a Principal Scientist and Head of the Genebank, ICRISAT, Patancheru, India, a position he still holds in the 'new organizational structure', where he has to manage the ICRISAT administrative Research for Development (R4D) portfolios with respect to management and utilization of genetic resources in crop improvement programs.

Hari knows very well that greater use of germplasm in crop breeding is the way forward for better conservation and use of genetic resources, and to address food and nutritional security in the developing world. As a principal scientist (in genetic resources), Hari performed exceedingly well, while promoting the greater use of genetic resources in crop improvement. Today, the representative subsets (i.e. the core and mini-core collections) of the ICRISAT crops (i.e. chickpea, groundnut, pearl millet, pigeonpea, sorghum, finger millet) and small millets (i.e. barnyard millet, foxtail millet, kodo millet, little millet, proso millet) have been made available, and globally researchers are using these subsets to identify new sources of variation to support crop breeding in their respective regions.

Hari's seminal work with Rodomiro Ortiz on the process and concept of forming the mini-core collection has been recognized as an 'International Public Good'. Hari has published a total of 812 articles, of which 291 have undergone international peer review. These include research articles, commissioned reviews, and book chapters, and he has averaged 11.6 such articles per year, with three articles per year as first author. Twenty-seven cultivars of groundnut that were bred by Hari are being cultivated in 18 countries in Africa and Asia.

Over my long association with Hari, I have found him to be a person with the highest scientific competence and integrity, and a successful plant breeder and genebank manager. Hari's leadership in managing one of the largest Consultative Group on International Agricultural Research (CGIAR) Consortium genebanks is very much reflected in a recently concluded external review, when the panel remarked that '*The ICRISAT genebank is functioning to high technical and scientific standards, and is very good in comparison with other international genebank operations. The users of the ICRISAT genebank are satisfied and appreciation of the genebank is wide spread.*'

II. BIOGRAPHICAL SKETCH

Hari was born on 12th August 1953, in the small village of Shiwala, in Khair Tehsil, District Aligarh, Uttar Pradesh, India. He is the seventh of the eight children of Mr Gopi Chand Upadhyaya and Mrs Longsri Devi Upadhyaya. He passed his high school examinations (X standard) with Biology as his main subject, and got a distinction in Mathematics. Hari did a BSc (with honours) at Aligarh Muslim University, Aligarh, India, and then moved to the GB Pant University of Agriculture and Technology, Pantnagar, India, to complete his MSc and PhD, both in Plant Breeding. Hari is married to Ms Sudha, and is blessed with two sons, Abhisheik Deo and Aaditya Deo. Interestingly, neither of his sons has followed in his footsteps, as they chose Information Technology for their career path. Hari derives great strength from his wife and children in his scientific endeavours.

III. CONTRIBUTIONS

Unlike traditional germplasm botanists and curators, whose vision is always centred on collection, conservation, characterization and documentation of germplasm, Hari's basic training in plant breeding and genetics helped him to think beyond routine genebank activities, to include enhancing the value of genetic resources in the breeder's perception. Plant breeders are often reluctant to use exotic germplasm, largely because of the fear of linkage drag, breakdown of co-adapted gene complexes, and lengthening of the breeding cycle for the development of new cultivars. Hari strongly believes in promoting the use of germplasm in crop improvement programs, the generation and use of new knowledge (i.e. physiological, genetic, molecular) of trait expression and inheritance in applied breeding, and the sharing of breeding populations and advanced varieties, and also of knowledge, to help the global community to increase the production and productivity of staple food crops. Hari invested heavily to add value to the germplasm collections, and uses this in the crop breeding at ICRISAT and in the national programs globally.

A. Genetic Resources Management and Use

1. Representative Subsets. The use of germplasm in crop improvement programs globally is restricted due to:

(i) the large sizes of collections of many crop species;
(ii) the non-availability of representative subsets; and
(iii) the lack of accurate and precise information on the agronomic worth of individual germplasm.

Hari saw the need, as advocated by Frankel and Brown (1984) to form reduced subsets that represent the diversity of the entire collection of a given species preserved in the genebank, and he initiated work to develop representative sets for ICRISAT mandate crops and small millets. Using passport and characterization data and statistical tools, Hari first developed the core collections (10% of the entire collection of a species stored in the genebank) for chickpea and, later, for pigeonpea, groundnut, pearl millet, and small millets (Table 1.1).

Table 1.1. Core collections formed by Hari Deo Upadhyaya in chickpea, groundnut, pearl millet, pigeonpea, and small millets.

Crop	Number of accessions used	Number of traits involved	Number of accessions in core	Reference
Pearl millet	20,766	22	2,094	Upadhyaya *et al.*, 2009a
Chickpea	16,991	13	1,956	Upadhyaya *et al.*, 2001a
Pigeonpea	12,153	14	1,290	Reddy *et al.*, 2005
Groundnut	14,310	14	1,704	Upadhyaya *et al.*, 2003
Finger millet	5,940	14	622	Upadhyaya *et al.*, 2006c
Foxtail millet	1,474	23	155	Upadhyaya *et al.*, 2008b
Proso millet	833	20	106	Upadhyaya *et al.*, 2011i
Barnyard millet	736	21	89	Upadhyaya *et al.*, 2014c
Kodo millet	656	20	75	Upadhyaya *et al.*, 2014c
Little millet	460	20	56	Upadhyaya *et al.*, 2014c

The chickpea core collection consisted of 1,956 accessions that had been selected from 16,991 accessions (Upadhyaya *et al.*, 2001a). Rodomiro Ortiz, the then Director of Genetic Resources and the Enhancement Program, ICRISAT, challenged Hari and Paula Bramel (a co-author with Hari) about how useful the core collections were, with such large numbers of accessions for screening a desired trait for further use in breeding. After evaluating 1,956 accessions, together with controls for one season, in an augmented design, Hari concluded that it was a Herculean task to accurately and cost-effectively generate datasets even for the core collection accessions.

Hari and Rodomiro Ortiz discussed this and adopted the approach of re-sampling the core collection to define a ‘core of the core’ or ‘mini-core’, subset. Here, they used the evaluation data (22 morphological and agronomic traits) of the core collection (1956 accessions) and statistical theory to sample the variability to form the mini-core collection (211 accessions) in chickpea. This represented the diversity that was present in the core collection, and also the entire collection, as shown by the similar means, variances, frequency distributions and preserved co-adapted gene complexes, both for the core and mini-core collections (Upadhyaya and Ortiz, 2001).

Hari and Rodomiro jointly wrote a manuscript on the chickpea mini core collection, with Rodomiro as corresponding author, and submitted it to *Theoretical Applied Genetics*. To their surprise, exactly two weeks later, they got a response from the editor to say that the manuscript was accepted for publication. This development encouraged Hari to follow this approach, and in subsequent years, he developed mini-core collections for other crops as well (Table 1.2). In all cases, both the core and mini-core collections fulfilled the statistical tests for the preservation of

Table 1.2. Mini-core collections formed by Hari Deo Upadhyaya in chickpea, groundnut, pearl millet, pigeonpea, sorghum, and small millet.

Crop	Entire collection	Mini-core number	% of entire collection	Traits used	Reference
Sorghum	22,473	242	1.08	21	Upadhyaya *et al.*, 2009b
Pearl millet	20,766	238	1.14	18	Upadhyaya *et al.*, 2011l
Chickpea	16,991	211	1.24	22	Upadhyaya and Ortiz, 2001
Pigeonpea	12,153	146	1.2	34	Upadhyaya *et al.*, 2006e
Groundnut	14,310	184	1.28	34	Upadhyaya *et al.*, 2002a
Finger millet	5,940	80	1.34	20	Upadhyaya *et al.*, 2010c
Foxtail millet	1,474	35	2.37	21	Upadhyaya *et al.*, 2011e

means, variances, and frequency distributions, and the co-adapted gene complexes of the entire collections (in the case of the core collections) or core collections (in the case of the mini-core collections).

2. Climate-resilient Germplasm. Global warming is putting significant stress upon agricultural production and the nutritional quality of staple crops in many parts of the world. Southern Asia and Sub-Saharan Africa will be the most adversely affected regions, due to climate change and the variability effects. ICRISAT-mandated crops are widely grown and consumed in these regions (http://faostat.fao.org/site/567/default.aspx#ancor).

The identification and use of climate-resilient germplasm in crop breeding is the way forward to develop 'climate-smart' crop cultivars. Hari adopted a two-pronged strategy, first by working with ICRISAT researchers, and second by providing the seeds of several sets of mini-core collections to NARS partners and working with them to evaluate these subsets for agronomic traits, including stress tolerance. The end result was the identification of several sources of resistance to abiotic and biotic stresses in chickpea and groundnut, with some accessions combining stress resistance and tolerance in good agronomic backgrounds (Upadhyaya *et al.*, 2013a, 2014d). Using a similar approach, Hari and his colleagues identified a number of drought-tolerant and salinity-tolerant germplasm accessions in finger millet and/or foxtail millet (Krishnamurthy *et al.*, 2014a, 2014b, 2016).

Blast (*Pyricularia grisea*) is a devastating disease in pearl millet and finger millet, which has many pathotypes. The work of Hari and his colleagues on screening the pathogenic variability led them to identify accessions that were resistant to multiple pathotypes in pearl millet (Sharma *et al.*, 2015), finger millet (Babu *et al.*, 2013b, 2015) and foxtail millet (Sharma *et al.*, 2014). Downy mildew (*Sclerospora graminicola* [Sacc.] Schröt) is a highly destructive and widespread disease of pearl millet, while grain mould and downy mildew (*Peronosclerospora sorghi*) are also important diseases of sorghum. Hari and his colleagues identified a number of accessions with resistance to multiple pathotypes in pearl millet (Sharma *et al.*, 2015) and sorghum (Sharma *et al.*, 2010, 2012). In addition, they identified some lines with good agronomic value, such as early maturity and resistance, and resistance and high seed/fodder yield potential, in both finger millet and pearl millet.

3. Seed Nutrient-dense Germplasm. Widespread micronutrient malnutrition in human beings, as a result of deficiency of iron (Fe), zinc (Zn) and β-carotene, has an enormous socio-economic cost for society in the developing world (Stein, 2010). Hari saw the need to identify seed nutrient-dense (i.e. Fe, Zn) germplasm to support crop breeding. After evaluating the mini-core collections for two seasons, Hari identified a number of different germplasm sources with high seed Fe and/or Zn concentrations in groundnut (Upadhyaya *et al.*, 2012d), pearl millet (Rai *et al.*, 2015), sorghum (Upadhyaya *et al.*, 2016c), finger millet (Upadhyaya *et al.*, 2011d), and foxtail millet (Upadhyaya *et al.*, 2011e). Finger millet and foxtail millet are rich sources of seed protein and calcium (Ca), with some accessions in both of these crops showing exceptionally high protein and Ca contents (Upadhyaya *et al.*, 2011d, 2011e).

4. Bioenergy. Sorghum is a crop that is used for food, feed, and bioenergy. The stalks are rich in sugar (as measured by Brix). However, the stalk sugar content is greatly influenced by the environment and the crop stage at which the stalks are harvested. Hari evaluated the sorghum mini-core collection accessions for stalk sugar content for two post-rainy seasons under irrigated and drought-stressed conditions. He found that drought stress significantly increased the mean Brix by 12–27%. A few germplasm lines had significantly greater mean Brix (14.0–15.2%), but were agronomically inferior, while some others were agronomically comparable but with similar Brix, such as IS 33844 (Brix, 12.4%) (Upadhyaya *et al.*, 2014a). This indicated that it is possible to select for even higher Brix content in agronomically superior genetic background in germplasm collections. IS 33844 is the local landrace *Maldandi* that was collected from Maharashtra, India, and it is the most popular sorghum cultivar that is widely grown under decreasing soil moisture conditions during the rabi (post-rainy) season in India. IS 33844 is tolerant to terminal drought and has excellent grain quality.

5. Germplasm Use in Breeding. Plant genetic resources are the basic raw materials for genetic progress, and they provide insurance against unforeseen threats to agricultural production. Hari firmly believes that the use of germplasm in crop improvement is one of the most sustainable ways to conserve valuable genetic resources and to broaden the genetic base of crops. Hari partnered with researchers globally to get these subsets (Tables 1–2) evaluated for stress tolerance, yield and seed nutritional traits, and collaborated with molecular biologists to dissect out the population structure and diversity in these representative subsets. This exercise resulted in the identification of several agronomically beneficial and genetically diverse germplasm sources that fulfil the needs of crop breeders. Armed with this valuable information, Hari interacted with crop breeders at ICRISAT and elsewhere, to promote the use of such germplasm in breeding programs.

An analysis of the uptake of germplasm in crop improvement programs at ICRISAT showed that germplasm use has increased since the formation of the mini-core collections in some crops. For example, there was increased use (≈15% increase) of stress-tolerant chickpea germplasm during the 2000–2004 and 2005–2009 periods, while in recent years (i.e. 2010–2014), more emphasis (22% increase) has been on the use of germplasm that has agronomic (yield *per se*) and seed nutritional traits. The trend noted in groundnut was opposite: namely, more emphasis (17% increase) on the use of yield and quality-enhancing germplasm from 2000–2004, which changed to increased (42% increase) the use of stress-tolerant germplasm from 2005–2009, with emphasis (46% increase) from 2010–2014 on stress tolerance, yield, and quality enhancement. All of this was possible because of the consistent efforts led by Hari and his colleagues (including those from ICRISAT and NARS countries) to use representative subsets in the identification of new sources of variation with agronomically beneficial traits, and to promote the breeders' willingness to use new germplasm as a resource in crop breeding.

6. On-farm Conservation and Use of Diversity. On-farm conservation and evaluation of genetic resources provides farmers with the opportunity to select germplasm adapted to their climate conditions. In addition, it also allows evolution of new genetic variants as a result of climate change and variability effects. This facilitates greater and more rapid dissemination of promising seeds among the farming community. Hari's collaborative work with NARS partners on the evaluation of core/mini-core collections of finger and foxtail millets, through a project on farmers' fields in Africa and Asia, provided the farmers with opportunities to access and appreciate the diversity of these neglected crops. Today, farmers own and cultivate some finger millet germplasm sources, such as IE 2440 and 4625 in Uganda, and IE 2872 and 4115 in Kenya, or finger millet (e.g. IE 3575, 4415, 4425, 6045, 6337) and foxtail millet (e.g. ISe 156, 1575) in India. In addition, the NARS partners from these countries have identified stress-tolerant germplasm that they are using in breeding programs to enhance the genetic potential of these crops.

7. Wild Relatives and Cultigen Genepool. Wild relatives and their derivatives are sources of variation for agronomic traits, which include stress tolerance, yield, and seed quality. Wild *Cicer* species, and particularly those from secondary and tertiary genepools that have high levels of resistance to stress tolerance, require vernalization and/or extended day-length treatments to synchronize their flowering with cultivated chickpea, for interspecific crosses. The use of vernalization and/or photoperiod response enabled Hari and his colleagues to introduce synchronized flowering into a few *Cicer* species, similar to that of cultivated chickpea (Sharma and Upadhyaya, 2015a). This contributes significantly not only to enhanced use of *Cicer* species for chickpea improvement, but also to improvements in the regeneration efficiency of *Cicer* species and their rapid generation turnover.

Cajanus albicans (Wight & Arn.) van der Maesen is a species from the secondary genepool of pigeonpea, and it is known for the long life of its large leaves (leaflet length, 4.4–6.8 cm; leaflet width, 3.1–5.8 cm). Hence, it is an important source of animal feed in semi-arid tropical regions. It possesses broader pods (9.6–15.0 mm) and high seed numbers (5–7 per pod), is resistant to abiotic (e.g. drought, salinity) and biotic (e.g. pod fly, pod wasp, *Alternaria* blight, sterility mosaic) stresses, and its high seed protein content (up to 32%) make it particularly attractive (Figure 1.1). Hari had to wait for about 500 days to see

Figure 1.1. *Cajanus albicans*, a wild species from a secondary genepool with many desirable characteristics, and a potential source for gene introgression in cultivated pigeonpea.

the flowering in *C. albicans*, and another 50–58 days to harvest the mature pods to complete the characterization data on this species. Notably, this produces partial fertile hybrids (Mallikarjuna *et al.*, 2011 and references therein), thus, providing a potential source to broaden the cultigen genepool in pigeonpea.

8. Gaps in Collections. Identifying gaps in collections and enriching collections with new sources is a critical function of genebank curators. Hari's work on gap analysis, using geo-referenced pearl millet landraces from Asian countries (5,768 accessions), revealed parts of the Bihar, Madhya Pradesh, Maharashtra, Rajasthan, and Uttar Pradesh provinces of India as the major geographical gaps in the world collection of pearl millet at ICRISAT (Upadhyaya *et al.*, 2010b).

His similar studies involving pearl millet landraces from southern and eastern Africa (3,750 accessions), and those from west and central Africa (6,434 accessions) also allowed Hari to identify regions in Africa that were not fully represented in ICRISAT collection (i.e. central Sudan and Tanzania, eastern Botswana, west and central Zambia, eastern and central Zimbabwe, southern Mauritania, Niger and Chad and northern Benin, Ghana, and Nigeria) (Upadhyaya *et al.*, 2009c, 2012f). Based on this gap analysis by Hari and requests from NARS partners, the ICRISAT regional genebanks in Africa organized collection missions and collected 6,625 new samples of mandate crops from west and central Africa and southern and eastern Africa regions. These, in my opinion, are important milestones achieved by Hari and his group that further enriched the germplasm collection at ICRISAT.

Hari's work further revealed that when landraces from the 5°–10°N latitude regions were grown at Patancheru, India, these flowered late and grew tall, and they also produced more tillers. Conversely, those from the 10°–15°N latitude regions had fewer tillers, but with long and thick panicles and larger seeds. Also, landraces from the 10°–15°S and 20°–25°S latitudes are good sources of resistance to bird damage (long-bristled panicle). Furthermore, Hari found that the landraces of the lower latitude regions (<20°N and S) in both hemispheres are better sources of fodder types (i.e. high tillering, tall, long duration), while those from mid-latitude regions (15°–20°) in both hemispheres are good sources for enhancing productivity (i.e. early, long and thick panicle, large seeds). Similarly, landraces on both sides of the equator (i.e. within the 10°–20° latitudes) are highly sensitive to the photoperiod (>12.5 hours) and/or temperature (<12 °C), while those from higher latitudes (20°–35°) in both hemispheres showed low sensitivity to both the photoperiod and temperature. The photoperiod and temperature insensitive accessions are represented mostly from the mid-latitudes (15°–20°) in both hemispheres (Upadhyaya *et al.*, 2012e, 2014f).

B. Molecular Biology and Biometrics

1. Population Structure and Diversity. Understanding how diversity is structured so as to unlock its potential for crop improvement is an emerging area that has been made possible by rapid advances in the scale, robustness, and reliability of marker technologies, and the sharp fall in the unit costs of their deployment. Hari is probably one of the few CGIAR scientists who used Generation Challenge Program (www.generationcp.org) grants to develop global composite collections, which the molecular biologists at ICRISAT genotyped using high-throughput assays and simple sequence repeats (SSRs). Hari then used genotyping data and his statistical knowledge to form reference sets in chickpea, pigeonpea, groundnut, pearl millet, sorghum, finger millet and foxtail millet. These reference sets accounted for 78–95% of the allelic variations observed in global composite collections (Table 1.3). Genotyping of reference sets has revealed abundant allelic diversity that grouped the accessions into distinct clusters, with many of the alleles unique in a particular accession in each crop (Upadhyaya *et al.*, 2008a; Billot *et al.*, 2013). This can be further explored, possibly to associate such allelic diversity with temporal and eco-geographical diversity, or in proprietary germplasm protection.

2. Genome-wide Association Mapping. The diversity panels of germplasm collections, such as the conventional core and mini-core collections, or genotype-based reference sets, are ideal germplasm resources for studying linkage disequilibrium and association mapping in crop plants. Identification of candidate genes associated with abiotic stress responses will accelerate breeding efforts that are aimed at enhancing productivity in drought-stressed environments.

Hari's collaborative work with molecular biologists led to the identification of 18 single nucleotide polymorphisms (SNPs) in chickpea reference accessions that were significantly associated with drought-avoidance root traits, carbon isotope discrimination, heat tolerance, harvest index, and 100-seed weight under drought-stressed conditions (Roorkiwal *et al.*, 2014a). Similar work using SSRs in groundnut reference accessions revealed significant marker-trait associations for drought-tolerance traits (e.g. chlorophyll readings, harvest index) and seed weight, under both well-watered and drought-stressed conditions (Pandey *et al.*, 2014).

Table 1.3. Composite collections and reference sets formed by Hari Deo Upadhyaya in chickpea, groundnut, pearl millet, pigeonpea, sorghum, finger millet, and foxtail millet.

		Composite collection		Reference set		
Crop	Number of SSRs used	Number of accessions	Number of alleles	Number of accessions	Number of alleles [*n* (%)]	Reference
Sorghum	41	3367	783	383	613 (78.3)	http://genebank.icrisat.org/GB_ReferenceSet/ReferenceSet_Sorghum.aspx; Billot *et al.*, 2013
Pearl millet	19	1021	230	300	218 (94.8)	http://genebank.icrisat.org/GB_ReferenceSet/ReferenceSet_Pearlmillet.aspx
Chickpea	48	2915	1683	300	1315 (78.1)	http://genebank.icrisat.org/GB_ReferenceSet/ReferenceSet_Chickpea.aspx; Upadhyaya *et al.*, 2008b
Pigeonpea	20	952	197	300	187 (94.9)	http://genebank.icrisat.org/GB_ReferenceSet/ReferenceSet_Pigeonpea.aspx
Groundnut	21	852	490	300	466 (95.1)	http://genebank.icrisat.org/GB_ReferenceSet/ReferenceSet_Groundnut.aspx
Finger millet	20	959	231	300	206 (89.2)	http://genebank.icrisat.org/GB_ReferenceSet/ReferenceSet_Fingermillet.aspx
Foxtail millet	19	452	362	200	316 (87.3)	http://genebank.icrisat.org/GB_ReferenceSet/ReferenceSet_Foxtailmillet.aspx

Together with his US collaborators, Hari identified significant marker-trait associations for phenology, panicle architecture and stress tolerance in sorghum, using diversity panel germplasm (Lasky *et al.*, 2015; Morris *et al.*, 2013; Upadhyaya *et al.*, 2012g, 2012h; Upadhyaya *et al.*, 2013f, 2013g, 2013h; Upadhyaya *et al.*, 2016f), which also included the sorghum mini-core collection accessions formed at ICRISAT (Upadhyaya *et al.*, 2009b).

3. Candidate Genes Associated with Agronomically Useful Traits. The discovery of large-scale high-quality SNPs led Hari and his collaborators to identify candidate genes that can regulate complex agronomic traits, such as flowering (e.g. *efl1*, *FLD*, *GI*, *Myb*, *SFH3*, *bZIP*, *bHLH*, *SBP*) (Upadhyaya *et al.*, 2015a), plant height (Kujur *et al.*, 2016), number of branches (e.g. *PIN1*, *TB1*, *BA1/LAX1*, *GRAS8*, *ERF*, *MAX2*, lipase) (Bajaj *et al.*, 2016b), number of pods and seeds per plant (Kujur *et al.*, 2015b), seed colour (e.g. *MATE*) (Bajaj *et al.*, 2015a), 100-seed weight (e.g. *CSN8*, *ERF*, *TF*) (Bajaj *et al.*, 2015b; 2015c, 2016a; Das *et al.*, 2015a), and seed protein (e.g. zinc finger transcription factor) (Upadhyaya *et al.*, 2016a) in chickpea.

4. Ethnolinguistic Groups Shaped Sorghum Diversity in Africa. Sub-Saharan Africa, and more particularly Ethiopia, Sudan, and Chad, were the primary centres of the origin and domestication of sorghum. Hari's collaboration with researchers from Norway and Sudan highlighted three major sorghum populations that were associated with the distribution of ethnolinguistic groups in Africa (Westengen *et al.*, 2014). The co-distribution of the central sorghum population and the Nilo-Saharan language family demonstrated a close and causal relationship between the distribution of sorghum and languages in the region between the Chari and Nile rivers. The southern sorghum population was associated with the Bantu languages of the Niger-Congo language family, while the northern sorghum population was distributed across the early Niger-Congo and Afro-Asiatic language family areas with dry agroclimatic conditions. Furthermore, the genetic structure within the central sorghum population was associated with language group expansions within the Nilo-Saharan language family.

The Western-Nilotic ethnolinguistic group (e.g. the Pari people) provided a window into the social and cultural factors involved in the generation and maintenance of the continent-wide diversity patterns. The age-grade system is a cultural institution that was important for the expansive success of this ethnolinguistic group in the past, and it had a central role in the management of sorghum landraces. This continues to underpin the resilience of their traditional seed system, which supports the 'farming-language co-dispersal hypothesis', which proposes that farming and language families have moved together through population growth and migration (Diamond and Bellwood, 2003; Jobling *et al.*, 2013).

5. Genome Sequencing. Hari was involved in the sequencing of the reference genomes of chickpea (Varshney *et al.*, 2012b), pigeonpea (Varshney *et al.*, 2013), groundnut (Chen *et al.*, 2016) and pearl millet. Hari's interest in genome sequencing lies in finding and associating sequence variations that have agronomically beneficial traits. He believes these will improve the efficiency of genebank operations, with particular reference to conservation, regeneration and use of germplasm with unique characteristics in crop breeding. Hari is participating in the 3000-genomes project of chickpea, using a composite collection and 300-groundnut genomes with reference set accessions. He hopes that this will provide him with many opportunities to use sequence variations for efficient management and use of genetic resources.

C. Groundnut Breeding

At ICRISAT Patancheru India, Hari was initially involved in developing early-maturing (short duration; 90 days in the rainy season) and aflatoxin-resistant groundnut varieties. For a few years (2000–2001 to 2004–2005), Hari also managed the groundnut breeding research at ICRISAT Regional Research Centre, Lilongwe, Malawi. His focus in Malawi was to incorporate early-maturity and resistance to leaf spots and rosette disease into locally adapted cultivars from the eastern and southern African areas. In 2012, Shyam N. Nigam, Principal Scientist and leader of the Groundnut Breeding Unit, ICRISAT, retired from ICRISAT, and the management asked Hari to shoulder additional responsibility as Principal Groundnut Breeder to mentor the incumbent and to continue working on breeding for early-maturity, drought tolerance, aflatoxin resistance, and high oil content in groundnut.

1. Early Maturity. Developing early-maturing (i.e. 90 days), high-yielding groundnut varieties was one of several breeding objectives when groundnut was included in ICRISAT as one of its mandate crops in 1976. In the early days, the often-used early maturing source was a small-seeded germplasm line, Chico (ICG# 476), from Russia (Bailey and Hammons, 1975), although it provided only limited success in breeding early maturity into an improved genetic background. The most common breeding strategy adopted during that time was to plant segregating populations and harvest them when the crop received 1470° Cd (cumulative thermal time), which was equivalent to 90 days after sowing during the rainy season in Patancheru, India, while the advanced lines were stagger-harvested when the crop accumulated 1240° Cd (equivalent to 75 days during the rainy season) and 1470° Cd after sowing in Patancheru, India (Vasudeva Rao *et al.*, 1992).

The three things Hari did differently from his predecessors were:

(i) he diversified the sources of early maturity by identifying new and diverse ones (Upadhyaya *et al.*, 2006f);
(ii) he investigated the genetics of early flowering (first flower appearance, accumulation of 25 flowers) (Upadhyaya and Nigam, 1994); and
(iii) he started selecting for early maturity on an individual plant basis, instead of adopting bulk selection method of breeding, as was the practice during these early days.

Hari used segregating populations, harvested at pre-designated heat units (1470 °Cd) in Patancheru, India. He then imposed other selection criterion: selection based on percentage sound matured kernels (SMK%) and on uniformity of seed size and shape (Legumes program Annual Report, 1993). This two-way selection pressure paid rich dividends and, in a short time, he developed a large number of early maturing advanced varieties with potential yield as high as 3 tons ha^{-1} to 4 tons ha^{-1}, harvested at 1470 °Cd in Patancheru, India (ICRISAT Archival Report of Research Program on Grain Legumes 2012–2013, 2014).

Selecting for high oil content or large-seed size in an early maturity background with improved yield potential was a breeding challenge. Hari was, however, successful in combining early maturity and high oil content, or early maturity and large-seed size, in improved genetic backgrounds (ICRISAT 2014, 2015; Upadhyaya *et al.*, 2005b).

Ultra-susceptibility to foliar diseases (i.e. rust, late leaf spot) and lack of fresh seed dormancy were associated with early maturity, with the potential risk to seed germination if it rained during the harvest and if there was a delay in lifting the crop from the field. Hari was successful in combining early maturity and fresh seed dormancy (Upadhyaya *et al.*, 1997a, 2001e), or tolerance to rust and late leaf spot (Upadhyaya *et al.*, 2001d) in some varieties.

Post-rainy season groundnut in India coincides with early winter in peninsular India, and there was a need to combine cold tolerance at germination in an early maturing genetic background. Here, Hari used his remarkable good sense and sharp mind. On one fine morning during the winter season, he visited his groundnut breeding field together with his technician, as the crop was just emerging from the ground. He noted that some plots had early emergence while, in many others, even the soil crust was not broken.

Together with his technician, he noted these plots, and he regularly visited them for about two weeks. He observed that some lines also had greater seedling vigour in addition to early emergence, compared with the others. Both early emergence and greater seedling vigour helped Hari to identify cold-tolerant lines in groundnut. Following this, he picked up a breeding line, ICGV 92267, that combined early maturity, low temperature tolerance at germination (≤12 °C), and resistance to rust and late leaf spot (Upadhyaya *et al.*, 2002c). For many aspects, I consider that this was a remarkable development, to enhance the adaptation of groundnut in new areas where the temperature is low at planting.

2. Drought Tolerance. Hari carried forward the drought tolerant breeding populations/advanced breeding lines developed by Shyam N. Nigam to their logical conclusion, while also introducing new elements to enhance the drought tolerance in groundnut. For example, he identified additional sources of drought tolerance in good agronomic backgrounds (ICRISAT 2014, 2015), which he crossed with early maturing varieties to produce new breeding populations that combined early maturity with drought tolerance.

Hari continued to evaluate breeding populations/advanced varieties under rain-fed (i.e. no supplemental irrigation) and irrigated (i.e. fully irrigated) conditions in rainy seasons (June/July to October/November), and under irrigated and stress conditions (i.e. withholding alternate irrigations from 60 days after sowing) in post-rainy (October/November to March/April) seasons. He also selected varieties that showed high pod yield under drought-stressed environments, with no yield penalty under favourable environments. Hari developed a number of high-yielding and drought-tolerant varieties (ICRISAT 2014, 2015), and some of these are already in evaluation trials in national programs across Asia and Africa.

3. Aflatoxin Resistance. Aflatoxin contamination is a serious quality problem in groundnut, and this involves pod, seed coat and cotyledons as the three components:

(1) resistance to natural seed infection;
(2) *in vitro* seed colonization; and
(3) aflatoxin production by *Aspergillus flavus* needs to be combined (Nigam *et al.*, 2009).

The environmental factors (e.g. drought stress at time of pod development and maturity) and post-harvest processing (i.e. harvesting, drying, curing) and storage (i.e. mainly temperature, humidity) conditions largely influence the aflatoxin contamination in groundnut. Hari was successful with the combination of resistance to natural seed infection and/or *in vitro* seed colonization by *A. flavus* into an improved genetic background, some of which supported very low levels of aflatoxin contamination, with potential yields of 2.5 t ha^{-1} to 4.0 t ha^{-1} during the rainy and post-rainy seasons in Patancheru, India. However, he agreed that much more needs to be done (ICRISAT 2014, 2015; Rao *et al.*, 1995; Upadhyaya *et al.*, 2001c).

4. Farmers Participatory Varietal Selection. Hari firmly believes that the success of plant breeders depends on how they perceive what farmers need and how close the breeders can integrate such traits into new varieties. The opportunity to work with stakeholders (i.e. the farmers, consumers, traders) adds additional value to successful plant breeders. The Tropical Grain Legume project II (Monyo and Gowda, 2014), which was supported by the Bill and Melinda Gates Foundation (www.gatesfoundation.org), provided such a platform to many scientists in the CGIAR and NARS institutions, to test products/technologies under on-farm conditions with active participation from the farmers.

Working with farmers in India, Hari noted they preferred varieties that mature early, are stress-tolerant, have ease of harvest and shelling, and have uniformity of pod and seed characteristics. Three of the groundnut varieties among those bred by Hari were selected by the farmers, and later these were released in India: ICGV 00350 in Andhra Pradesh and Tamil Nadu; ICGV 00351 as ‘CO 7’ in Tamil Nadu; and ICGV 93468 as ‘Avatar’ in Uttar Pradesh. The first two were selected for drought tolerance and adaptation to both rain-fed and irrigated post-rainy season production systems, while the last one was adapted to spring season cultivation (February/March to June/July), especially after a harvest of potato in Uttar Pradesh.

This ‘Avtar’ cultivar has revolutionized groundnut production during the spring season in the Uttar Pradesh state of India. The acreage has expanded from a mere 20,000 ha in 2004 to 317,068 ha in 2011, and production during the same period increased from 53,100 t to 802,616 t; however, the average productivity remained at 2.53 t ha^{-1}. Shyam N. Nigam of ICRISAT and officials from the Department of Agriculture, Uttar Pradesh, India, contributed to the popularizing of ‘Avtar’ for cultivation during the spring season in Uttar Pradesh. Hari is now using the knowledge gained from the interaction with the farmers in the development of new cultivars with the traits preferred by the farmers, and he has several such products (varieties) in his cupboard that are waiting for the opportunity for on-farm evaluation and selection by the farming community.

D. Chickpea Breeding

Wilt caused by *Fusarium oxysporum* f.sp. *ciceris* is widespread, and causes substantial yield loss to chickpea production worldwide (Nene *et al.*, 1978). Early studies on the pathotypes revealed four races of wilt (Haware and Nene, 1982), with resistance to race 1 prevalent at Patancheru, which is controlled by a single recessive gene in crosses involving C 104 as the susceptible parent (Kumar and Haware, 1982). However, in the crosses with cultivar JG 62 as a susceptible parent, the number of susceptible plants was too large to give a good fit to the expected ratio.

Hari's seminal work on inheritance of wilt resistance revealed that the appearance of the wilting symptoms differed amongst the JG 62 and C 104 susceptible parents. C 104 wilts later than JG 62, whereby the difference in the time of wilting is controlled by a single gene, with early wilting partially dominant to late wilting (Upadhyaya *et al.*, 1983a). Here, further studies by Hari showed that the resistance is controlled by at least two genes, both of which must be present in their homozygous recessive forms to impart complete resistance (Upadhyaya *et al.*, 1983b) although, individually, the genes delay wilting, as in C 104. This discovery by Hari laid a strong foundation later on for the wilt resistance breeding program, which was one of the most successful chickpea disease-resistance breeding programs at ICRISAT, and indeed, elsewhere.

IV. UPADHYAYA, THE MAN

A. Personality

Hari comes from an agricultural family background. His father was a farmer, who was a highly religious and spiritual person. Hari has told me that he has been interested in plants and agriculture since his childhood, and he used to help his family in the field work. He enjoyed walking in wheat and mustard fields in the evening after school. His pet subjects were mathematics and biology, and his interest in these during his high school days was fortified by his teachers, Mr Naubat Singh (Mathematics) and Mr Brindavan Lal Verma (Biology). At Aligarh

University, he was greatly influenced by the teaching of his Plant Physiology Lecturer, Prof. MMRK Afridi. While at 'GB Pant' University of Agriculture and Technology, Pantnagar, he came into contact with Dr Bir Bahadur Singh, a well-known cowpea breeder (who had earlier worked as a soybean breeder at Pantnagar), with whom he conducted research for the partial fulfilment of his MSc and PhD degrees.

Hari's dream was to become a good plant breeder and to publish an article in *Crop Science*, a prestigious journal that many plant breeders aspired to in those days, especially those from developing countries. During his Postdoctoral Fellowship assignment, Hari learned the art of writing a good journal article from JB Smithson, the then Principal Chickpea Breeder at ICRISAT, while Shyam N. Nigam, the Groundnut Breeder at ICRISAT, Patancheru, India, provided him with strong administrative support and independence, so that he could apply his knowledge of genetics and breeding methods to the development of early-maturing and aflatoxin-resistant groundnut varieties. This has resulted in many groundnut cultivars with early maturity that are now being cultivated in several countries in Africa and Asia.

During his long academic career at ICRISAT, Hari worked with many colleagues, and also interacted with researchers from diverse institutions, each of whom now carries their lasting impressions about him as an outstanding researcher of the highest scientific competence and integrity (see their impressions in Boxes 1.1–1.4).

Hari and I worked for almost 24 years at ICRISAT, first on breeding (groundnut) and then on genetic resources, which provided me with many opportunities to follow the insights of Hari Upadhyaya, and I feel that it is appropriate if I mention a few of these here. As I know, Hari is a person 'who does not easily influence or make immature claims'. Groundnut is an important oil and food crop, which contains both oil (≈45%) and protein (≈25%) in the seed. In 2014, Hari found that some of his groundnut breeding lines had up to 61% oil. Initially, he did not believe this, and so he sent seed samples for re-analysis in another laboratory using nuclear magnetic resonance; this also showed high oil among these lines. He then had this rechecked using the Soxhlet method, and only then was he satisfied that these lines were exceptionally high in oil content.

Hari has a strong background in biometrics and quantitative genetics, and initiated genetic studies to determine the influence of epistasis in groundnut. He developed genetic populations using modified triple test crosses (Ketata *et al.*, 1976), wherein both the parents and their F_1 are crossed to germplasm lines to estimate epistasis. However, when he

Box 1.1. [Impression]

The first things that come into my mind about Hari is the self-confidence, dedication, and conscientiousness he shows as part of anything he does, be it research or a social activity. This is something of a rare commodity in the modern world, where people are more likely to do just what is required and leave the rest to fate or for others to handle. Although we studied in the same university (GB Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India), I left the University before he joined it and, hence, I met him only at ICRISAT during his interview, as I was a member of the Interview Panel. He still recalls the questions I asked, but what mattered is that he was selected and he joined to work at ICRISAT.

He was assigned to work on the genetics of resistance to fusarium wilt in chickpea. Many people would consider that this is a simple problem that would not require a full-time scientist. A year later, when the initial results were presented, many scientists (including the senior pathologists at ICRISAT) woke up and were forced to take note of the great discoveries made by Hari. Most plant breeders and pathologists who dealt with screening for fusarium wilt resistance considered only two symptoms in the seedlings or plants: wilted or healthy. It was only after Hari had dissected the wilt symptoms into a few differential and segregating populations that he coined the term 'late wilting'. We were told that Hari would take wilting scores every 2–4 hours to differentiate 'late wilting' from normal wilting, to make sure that he was not making any mistake. He also wanted to convince his supervisors (who did not believe him initially and who, indeed, scoffed at the concept of 'late wilting') that he could prove to them that there is a phenomenon called 'late wilting', and that it is a genetically controlled trait.

Hari had keen eyes to scan and find out if the data were curated properly or not, and whether they had been checked for accuracy before analysis to spot values that were out of the normal range, or outright incorrect data. I would rank him as one of the best plant breeders of our time, and regret that he did not get credit for what was due to him because of the jealousy of his peers, and because he shifted from a plant breeder to a germplasm botanist, and then returned to plant breeding almost a decade later. This discontinuity in groundnut breeding at ICRISAT HQ (which was not his desire, but was an executive decision by the institute management) potentially cost the institute many high-yielding and stress-tolerant cultivars that would have created greater impact (in addition to many improved varieties that have been adopted by farmers in Asia and sub-Saharan Africa). I have seen Hari spend 6–8 hours a day in a field during the crop season, taking observations himself (while most other plant breeders would delegate it to junior technicians) and making selections. These regular visits gave him very intimate knowledge of the groundnut crop, and helped him make appropriate selections at the right time.

Hari is very upright and talks straight. If something is not right, he will say so to your face, and not behind your back. His scientific competence and integrity is beyond doubt. He applies his highest value to rigorous scientific research, in terms of data quality and accuracy of observations. I have seen him going to fields late in the evenings, if he doubted some data taken by his staff, to verify it himself. He is a prolific writer, whose appetite for publishing research papers is huge. I encouraged this tendency in him, as it will leave his legacy in the scientific community for generations to come.

(Source: *Courtesy of CL Laxmipathi Gowda, former Deputy Director General, ICRISAT and currently Co-Founder, GRSV Consulting Services, Mysuru, India*)

Box 1.2. [Impression]

Hari has dedicated his career to the application of science and technology to improve staple food crops predominantly cultivated in the developing world. He embodies my personal concept of an ‘ideotype’ for a genetic resources scientist, combining deep-rooted experience with energy and enthusiasm for improving worldwide agriculture. Hari’s background in applied plant breeding shapes his thinking continually. He empowers others to improve crops by routinely and efficiently accomplishing the essential functions of a genetic resources scientist. However, he also reaches beyond these necessary functions, to increase knowledge of the gene pool in a manner that nurtures accelerated progress in crop improvement. His creative thinking makes him an early identifier of needs and opportunities, often nurturing the development of data that offer solutions before some of us fully appreciate the problem. His experience in field crop management positions him well to anticipate and mitigate the challenges that inevitably affect agricultural research undertakings. His high energy level, timely feedback and responses, open manner and engaging personality make him a pleasure to collaborate with.

My own interactions with Hari have been frequent over the past decade, in terms of peanut and sorghum research. We share a common interest in the development and use of novel germplasm. I have stated for more than a decade that the most important accomplishment that could be realized in peanut improvement was the use of synthetic polyploids to broaden the exceedingly narrow genetic base of this important crop. Lacking the skills to do this myself, it has been with tremendous excitement that I have watched Hari reach into this difficult problem and begin to use such novel germplasm. Hari has been among a select few who have most greatly advocated and encouraged the use of applied genomics for crop improvement, seeing that it can open doors to tapping germplasm resources that are presently inaccessible to crop scientists. A world without Hari's work would be much poorer, especially regarding the 'poorest of the poor', who are the primary beneficiaries from the improvements to the crops that Hari has worked on.

(*Andrew H Paterson, University of Georgia, Athens, Georgia, USA*)

Box 1.3. [Impression]

Hari Upadhyaya wanted to become a good plant breeder and to contribute to the ongoing green revolution in India. He was a fast learner, excelled in his studies, and made original contributions in the field of soybean genetics and breeding. His practical learning during the graduate program, coupled with his personal drive, self-motivation, devotion to his goal, and a quest for excellence, have allowed him to carve a path of excellence through his professional career, through which he has risen to be one of the best crop scientists in the world. Among his many scientific contributions, Hari has established a school of his own for the management, evaluation and use of genetic resources for crop improvement.

(*Bir Bahadur Singh, Texas A&M University, College Station, Texas, USA*)

Box 1.4. [Impression]

Hari's impact has been to leverage his unique vision for curation and management of the world's germplasm resources into a powerful tool that is approachable for, and has great relevance to, crop improvement. The ICRISAT genebank has the largest collection of its mandate crops and small millets. The sheer number of accessions was itself a deterrent to their effective use, because most breeders and plant biologists simply had no idea where to start. Which accessions to choose? How would one make such a decision to begin with? Hari's innovation was to understand how to solve this problem; in particular, to move from a situation where germplasm science was focused on curatorial, archival, and maintenance activities, to a situation where genebanks develop methods to enable rationale and frequent use of their stocks. The strategy that he devised, which seems simple in retrospect, was to organize the collections for each species into groups that reflected their functional potential. After all, breeders aim to extract function from the resources so, if one were able to assign the large number of individuals to a small number of functional groups, the task would be greatly simplified.

Hari's efforts have played out over the past two decades, when molecular sciences were accessible but laborious – a very different situation compared with today's technologies. This makes his team's contribution even more commendable. Working primarily within the ICRISAT system, Hari combined his vision with ICRISAT's capacity for phenotyping and molecular analyses. His goal was to reduce the large collections of each species into core collections that represent 10% of the total accessions. This first cut was largely based on the available phenotypic characterization and passport data. He then sought to further reduce these collections to 10% of the core (a 'mini-core', containing 1% of the total accessions), primarily through multi-season evaluation of the core collections combined with genotyping.

The simple logic of developing groups based on phenotypic and genetic diversity metrics, and then nominating individual accessions to represent these groups, provided an effective means to enrich for both functional and genetic diversity. At this point, the task turned to screening the cores and mini-cores at the phenotypic level for a variety of agronomic traits (e.g., drought and heat resistance, disease resistance, yield, and others). The outcome was another refinement, as the germplasm could then be organized as trait-specific subsets, whereby the nature of the subsets depends on the particular phenotypes that a breeder might be interested in.

The results of the efforts of Hari and his colleagues, which were based largely on Hari's vision, were transformative. Literally hundreds of thousands of samples have been distributed to breeders, crop scientists and molecular biologists throughout the world. His impact has been to transform the way we deal with germplasm, increasing the efficiency and logic with which functional variation is accessed and deployed for humankind.

(Source: *Courtesy of Douglas Cook, University of California, Davis campus, USA*)

received some analyzed results, he found that some of these did not follow along expected lines. He checked the raw data several times, but found no mistakes, so he sat down with his calculator and re-analyzed the data himself. He noted differences between his results and those that came from the Statistics Unit. He then discussed this with the programmer, and eventually prevailed upon him to correct the computer program. He then re-analyzed data, and the results were along the expected lines, as he had observed through his manual analysis. He published his first research article in 1998 on 'Epistasis for vegetative and reproductive traits in peanut' in *Crop Science* (Upadhyaya and Nigam, 1998). This was one of the two dreams that he wanted to achieve when he started his career as an agricultural scientist (as we remember, the other was to become a good plant breeder).

Hari inherited some F_2 seeds from me that were derived by crossing TxAG 6 (a synthetic originated through crosses involving three *Arachis* species (Simpson *et al.*, 1993)) with TMV 2 (an early maturing variety widely grown cultivar in peninsular India). When he grew 146 F_2 plants in pots, he noted that, although there were no problems in flowering and the plants looked good, the pegs did not enter the soil. He then grew large numbers of plants of TxAG 6 and observed every day for a month before he selected plant number 14, which was closer to the cultivated type than others. He used this plant as the pollen donor to cross with TMV 2.

The F_1 generation was genuine but, in the F_2, all of the 477 plants looked like those of TMV 2. He was heartbroken and checked with his technician, who confirmed that the cross was genuine. However, he continued to visit the facility where this large population was grown in

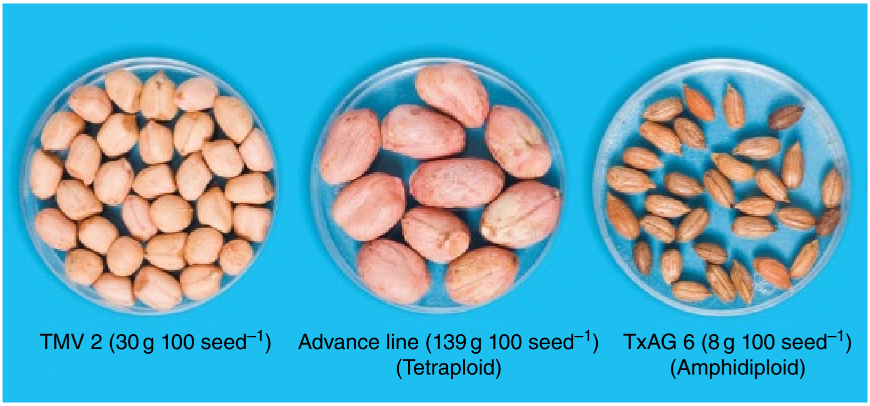

Figure 1.2. Cryptic genetic variation captured in groundnut by Hari Deo Upadhyaya that originated from a cross between TMV 2 (a leading groundnut variety in southern India) and amphidiploid (TxAG 6).

concrete rings, and he personally harvested individual plants separately. During harvesting, he noted that pod/seed traits of the F_2 plants (i.e. seeds per pod, pod beak, constriction and reticulation, and seed size) were different from those of TMV 2, and only then was Hari satisfied that the cross was genuine, whereby it showed abundant segregation for the pod/seed characteristics.

Finally, this population was stabilized, and he derived over 150 lines, most of which were similar to TMV 2 in all aspects except for foliage colour, chlorophyll content, pod yield and 100 seed weight. In repeated trials, several of these lines produced 25–30% greater pod yields, with some with 100-seed weights as high as 130 g (Figure 1.2) in the Spanish (subsp. *fastiggiata* var. *vulgaris*) background (Spanish germplasm does not have 100-seed weights > 75 g). Hari strongly believes that this exceptionally large seed size trait that he recovered originated as result of cryptic genetic variation.

B. Educator and Leader

Hari has an immense passion for teaching, and he can spend hours explaining the fundamentals of population genetics and the nuances of analysis and data interpretation. Hari taught a population genetics course to postgraduates at the University of Agricultural Sciences Dharwad, India; elementary genetics course to undergraduates at ‘GB Pant’ University of Agriculture and Technology, Pantnagar, India; and a genetics and advances in agricultural botany course at University of Agricultural Science, Dharwad, India. Hari has shown to the world that a genebank curator's role is not only confined to collection, maintenance, and archiving germplasm, but beyond this there exist abundant opportunities to mine and enhance the value of the genetic resources in crop improvement programs. Six of his students have conducted research using mini-core collections for their PhD theses.

C. International Collaborations

Hari has the amazing ability and scientific competence to collaborate with diverse groups and institutions across continents. He collaborates both nationally and internationally with diverse groups of researchers, both from developed and developing countries. He has developed strong links with many research programs, including the University of Agricultural Sciences, the National Bureau of Plant Genetic Resources, and with the Indian Council of Agricultural Research institutions in India. He also has links with universities in the USA (Texas A&M University, College Station and University of Texas, Texas; Kansas State University, Manhattan, Kansas; Columbia University, New York; Cornell University, Ithaca, New York; University of Georgia, Athens, Georgia; Louisiana State University, Lafayette, Louisiana; University of California, Davis, California; Clemson University, Clemson, South Carolina; New Mexico State University, New Mexico), and with the University of Western Australia, Crawley, Australia, and University Hohenheim, in Germany.

His collaborative research has revolved around the use of genetic and genomic resources in crop improvement, which has ranged from strengthening and managing germplasm collections and identifying trait-specific climate-smart germplasm through understanding the genetics, physiological, and molecular bases of trait expression and inheritance, to enriching and deriving strength from genomic sciences to enhance the use of germplasm in crop breeding at ICRISAT and elsewhere.

D. Recognition

1. Awards. Among the several awards Hari has received (Table 1.4), the most prominent include the prestigious 'Harbhajan Singh Memorial Award' for his outstanding contributions and great impact in the field of plant genetic resources in India, the 'Frank N Meyer Medal' for outstanding contributions of global significance to the conservation and use of plant genetic resources, the 'Crop Science Research Award', and the award for 'International Service to Crop Science Globally'.

Table 1.4. Some of the awards and honours received by Hari Deo Upadhyaya from 2002 to 2017.

Year	Award	Contribution	Awarding agency
2017	Fellow of National Academy of Agricultural Sciences	Outstanding contributions in groundnut breeding and plant genetic resources management	National Academy of Agricultural Sciences, India
2016	Honorary Fellow of Uttar Pradesh Academy of Agricultural Sciences, India	Outstanding contribution in the Management of Biodiversity	Uttar Pradesh Academy of Agricultural Sciences, India
2015	Harbhajan Singh Memorial Award	Biennium award for scientific excellence, leadership, outstanding contributions and great impact in the field of plant genetic resources (2013–2014)	Indian Society of Plant Genetic Resources
2014	International Service in Crop Science Award	Outstanding service to crop science globally	Crop Science Society of America
2014	Plaque of Appreciation	Outstanding contribution to VAAS-ICRISAT partnership in agricultural development	Vietnam Academy of Agriculture Sciences
2014	Certification of recognition	Outstanding contribution to NARC-ICRISAT partnership on the occasion of 40 years of NARC-ICRISAT R4D Partner celebration	Nepal Agriculture Research Council
2013	Frank N Meyer Medal	Outstanding contribution to global significance of the conservation and use of plant genetic resources	Crop Science Society of America
2013	Crop Science Research Award	Outstanding contribution to crop science research of global significance	Crop Science Society of America
2012	Honorary Fellow of Indian Society of Plant Genetic Resources	Outstanding contributions to the field of plant genetic resources leading to significant growth in agriculture	Indian Society of Plant Genetic Resources
2009	Millennium Science Award	Outstanding contribution 'collecting, preserving, characterizing, and distributing genetic resources of ICRISAT mandate species for use by all researchers in the world'	ICRISAT
2009	Fellow of Crop Science Society of America	Outstanding contribution in devising strategy for enhanced germplasm use by mini-core collection in dry land crops	Crop Science Society of America
2008	Fellow of American Society of Agronomy	Outstanding contributions in devising strategy for enhanced germplasm use by mini-core collection in dry land crops	American Society of Agronomy
2006	CGIAR Outstanding Science Award	Jointly shared with CLL Gowda and RP Thakur for 'Outstanding Partnership of the CGIAR Genebank Community'	CGIAR
2005	Doreen Mashler	Strategies for enhanced use of germplasm through improved early maturing groundnut in Asia and Africa	ICRISAT
2003	Millennium ICRISAT Outstanding Scientist Award	Contribution to 'reduction in poverty, hunger and malnutrition through sustainable increase in productivity by broadening the genetic base of crops and insuring against vulnerability to disease and pests'	ICRISAT
2002	Doreen Mashler	Outstanding contribution to chickpea improvement	ICRISAT
2002	King Baudouin Award	Jointly awarded to chickpea team (including Hari Upadhyaya) at ICRISAT and ICARDA for outstanding contribution to chickpea improvement	CGIAR

2. Honours. Hari Upadhyaya is a fellow of the Crop Science Society of America (CSSA), the American Society of Agronomy (ASA), the National Academy of Agricultural Sciences, India, and the Uttar Pradesh Academy of Agricultural Sciences, India and a member of the Fellows Committee of CSSA and ASA. He is a member of the Crop Science Research Awards Committee and the Seed Science Awards Committee of the CSSA, and Chair of the Seed Science Award and Crop Science Research Award Committees of CSSA (Table 1.4). Hari is currently an Adjunct Professor at the University of Western Australia and at Kansas State University, Manhattan, Kansas, USA.

3. Service. As well as being Secretary of the ICRISAT Plant Materials Identification Committee (PMIC), which clears the proposals for registration of elite genetic stocks in scientific journals, Hari also serves as member of the Controlled Environment Research Advisory Committee, Institutional Biosafety Committee, and Research Committee. Hari had a critical role in seeking approval from PMIC to facilitate the release of elite lines with unique characteristics (as both germplasm and advanced varieties). The Research Committee is a very powerful committee that advices the management group on ICRISATs R4D policies and priorities to ensure science quality, research excellence, and consistency with the strategic, business and medium-term plans of ICRISAT. Hari serves as Associate Editor of *Crop Science*, and has been a member of Advisory board/Editorial Board of *Akdeniz Univ. J. Fac. Agric.* (also known as *Mediterranean Agric. Sci.*), *EKIN Journal of Crop Breeding and Genetics, Field Crops Research*, and *The Scientific World Journal*. In addition, he also acts as Regional Editor of the *Asian Journal of Agricultural Sciences*, and Section Editor of the *Journal of Semi-Arid Tropical Agricultural Research* (*J. SAT Agric*).

V. PUBLICATIONS

Hari has published a total of 812 articles, of which 291 have been in international peer-reviewed journals, and they include journal articles, commissioned reviews, and book chapters. He has averaged 11.6 articles per year, with three articles per year as first author. Hari has co-authored several papers that are published in journals with high impact factors. In addition, Hari has co-authored several commissioned reviews on subjects as diverse as abiotic stress tolerance and transgenes, genomics and agrobiodiversity, global warming impacts on food, nutrition, and agrobiodiversity, haploids and plant breeding, host-plant and rhizobium genomics, landraces as source of abiotic stress adaptation, molecular breeding, phytochemicals and staple food crops, and pre-breeding. These have been well-received globally by the research community.

Hari's collaborative research has generated new knowledge (i.e. trait inheritance) and materials (i.e. genetic and genomic resources) of immense value to applied plant breeding. The genebank manual 'Managing and Enhancing the Use of Germplasm – Strategies and Methodologies', which he co-authored with CL Laxmipathi Gowda, is widely referred to by researchers globally to manage the genetic resources of ICRISAT mandate crops and small millets. Likewise, NARS researchers have found an Information Bulletin 'Mini-Core Collections for Efficient Utilization of Plant Genetic Resources in Crop Improvement Programs' very handy for the development of similar germplasm collections in other crops. Hari has co-edited three books, one exclusively on sorghum, and the other two on genetics and genomic resources of cereals and legumes.

VI. PRODUCTS

A. Cultivars

As a groundnut breeder, Hari developed 27 cultivars (ICGV#) that have been released in 18 countries (Table 1.5), some with wide adaptation. For example, ICGV 86015 was released in Nepal, Niger, Pakistan, Sri Lanka, and Vietnam; ICGV 93437 in Mozambique, South Africa, Zambia, and Zimbabwe; and ICGV 86143 in India, Vietnam, and Zambia. An early maturing (90–95 days in the rainy season), drought-tolerant (both mid-season and end-of-season droughts) and foliar disease-tolerant (rust, late leaf spot) cultivar, ICGV 91114 is becoming very popular in the Andhra Pradesh, Maharashtra, Odisha, and Telangana provinces of India (Figure 1.3). Some of the recent releases (ICGV-SM#) from the ICRISAT Regional Program in Malawi have the distinct stamp of Hari's selections (Table 1.5).

B. Registrations

Hari has registered 24 elite germplasm lines in groundnut that show agronomically beneficial traits, such as: early maturity (Nigam *et al.*, 1995; Upadhyaya *et al.*, 1998, 2002c, 2002d); early maturity and fresh seed dormancy (Upadhyaya *et al.*, 1997a, 2001e); early maturity and large seed size (Upadhyaya *et al.*, 2005b); early maturity and lower susceptibility to rust (Upadhyaya *et al.*, 2001d); early maturity and lower susceptible to rust and late leaf spot and tolerance to low temperature at germination (Upadhyaya *et al.*, 2002c); early maturity

Table 1.5. List of 27 groundnut cultivars and their local names released in 18 countries in Africa and Asia.

Country	Variety	Country	Variety
Bangladesh	ICGV 94322 (Barichinab-adam-8)	Nepal	ICGV 86015 (Jayanti)
	ICGV 96342 (BARI Chinabadam-9)	Niger	ICGV 86015
	ICGV 96346	Pakistan	ICGV 86015 (BARD 92)
India	ICGV 86143 (BSR 1)	Philippines	ICGV 00350
	ICGV 92195 (Pratap Mungphali-2)	South Africa	ICGV 93437 (Nyanda)
	ICGV 91114 (Devi)	Sri Lanka	ICGV 86015 (Tikiri)
	ICGV 93468 (Avtar)	Tanzania	ICGV-SM 01711
	ICGV 00348		ICGV-SM 01721
	ICGV 00350	Timor Leste	ICGV 95278
	ICGV 00351 (Co7)	Uzbekistan	ICGV 86155 (Salomat)
	ICGV 00298	Vietnam	ICGV 86143 (LO5)
	R-8808 (Apoorva)		ICGV 86015 (HL 25)
Malawi	ICGV-SM 01514	Zambia	ICGV 86143 (MGS 2)
	ICGV-SM 01724		ICGV 93437 (Nyanda)
	ICGV-SM 01731		ICGV-SM 03517 (Wamusanga)
Mali	ICGV 86015	Zimbabwe	ICGV 93437 (Nyanda)
Mozambique	ICGV 93437 (Nyanda)		ICGV 94297 (Ilanda)
	ICGV-SM 01513		
	ICGV-SM 01514		
Myanmar	ICGV 93382 (Sinpadetha 7)		
	ICGV 94301 (Sinpadetha 8)		
	ICGV 94361 (Sinpadetha 9)		

Figure 1.3. ICGV 91114, an improved groundnut variety that was developed by Hari Deo Upadhyaya and shows early maturity (90 days), drought tolerance and resistance to rust and late leaf spot, which is now popularly grown in India.

and lower susceptibility to peanut bud necrosis disease (Dharamraj *et al.*, 1996); and resistance to natural seed infections, *in vitro* seed colonization, and with low levels of aflatoxin contamination by *A flavus* (Rao *et al.*, 1995; Upadhyaya *et al.*, 2001c). These elite germplasms/varieties are available to researchers globally after signing the Standard Materials Transfer Agreement with ICRISAT.

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