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Present status and future prospects of garlic (*Allium sativum* L.) improvement in India with special reference to long day type

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Abstract
Garlic is grown throughout the world but the crop invariably suffers from productivity lower than its potential, owing to several inherent and extrinsic factors, especially in developing countries like India. The objectives of garlic improvement, thus, should be induction of sterility, creation of variability and molecular elucidation of genome for breeding superior cultivars adapted to different agro-climatic environments; and establishment of effective biotic and abiotic stress management and post harvest practices adoptable by resource poor farmers and suitable for sustained ecological well being. In Indian context, the improvement and cultivation of long day type garlic needs to be encouraged to commensurate with world leaders in production. Therefore, this review has been attempted to bring together the achievements made in garlic research in India and elsewhere, and their possible applications in attaining desired productivity and quality in both short and long day types.

Keywords: *Allium sativum*, Garlic, Long day, Sterility, Apomixes

Introduction
Garlic (*Allium sativum* L.) is a world's favorite, versatile horticultural commodity consumed for culinary, medicinal and antimicrobial purposes and is being cultivated for 5000 years [1, 2]. The aroma in garlic is due to volatile organosulfur compound 'Allicin' that makes it popular in daily cooking in Indian household and rest of the world, especially, Asia and the Mediterranean region. Its medicinal value has been appreciated especially, in the Unani and Ayurvedic systems of medicine for digestive system disorders, blood cholesterol, sterility, cough etc [3, 4, 5]. The antibacterial action by virtue of allicin has been found to have potential even in organic farming for treatment of plant diseases [6].

The principle producers of garlic are China, Egypt, India, Turkey, South Korea and Spain. In India, garlic is commercially cultivated throughout the country. But the long day garlic is cultivated only in temperate region especially in Jammu and Kashmir, Himachal Pradesh, and Uttarakhand. This type requires long photoperiod (13+ hours) with warm temperature (20-25 °C) for bulbing. In temperate India, the planting time for long day garlic falls around September-October. The increase in day length from around February following the decline in snowfall and rise in temperature till the month of May is congenial for bulbing and bulb development.

Area and Production
According to 2014-15 estimates of horticultural statistics by NHB, the three major garlic growing states of India were Madhya Pradesh (60,000 ha), Rajasthan (45,000 ha) and Uttar Pradesh (37,200 ha) and the highest production was seen in Madhya Pradesh (270,000 t), followed by Gujarat (250,000 t) and Rajasthan (218,400 t). The highest productivity was shown by Punjab (12.16 t/ha), followed by West Bengal (11.94) and Maharashtra (11.43). The long day garlic is, however, cultivated by states of Himachal Pradesh, Uttarakhand and Jammu and Kashmir only but on very small area. efficient use of the technology. On the other hand, sincere efforts should be made for the development and release of hybrids.

Table 1: Area, production and productivity of garlic in India (2014-15)

State	Area ('000 ha)	Production ('000 MT)	Productivity (ton/ha)
Madhya Pradesh	60.00	270.00	4.50
Gujarat	35.00	250.00	7.14
Rajasthan	45.00	218.40	4.85
Uttar Pradesh	37.20	218.20	5.86
Assam	10.10	69.40	6.89
Punjab	3.70	45.00	12.16
Maharashtra	3.50	40.00	11.43
West Bengal	3.40	40.00	11.94
Haryana	4.40	35.80	8.07
Odisha	10.90	35.50	3.26
India (approx.)	230.60	1251.90	5.43

Source: National Horticulture Board advanced Estimates for 2015 (NHB) [7]

Although India stands second in area and production of garlic but its productivity (5.69 t/ha) is strikingly far below China and Egypt, which have almost five times the productivity of India. These countries are closely followed by USA and Republic of Korea.

Table 2: Area, production and productivity of garlic in the world (2014)

Country	Area (lakh ha)	Production (lakh MT)	Productivity (MT/ha)
China	7.91	200.58	25.36
India	2.31	12.52	5.42
Republic of Korea	0.25	3.54	14.16
Egypt	0.11	2.63	23.91
Russian Federation	0.28	2.56	9.14
Bangladesh	0.53	3.12	4.42
Ethiopia	0.09	0.93	10.33
Myanmar	0.28	2.09	7.46
USA	0.10	1.75	17.50

Source: FAOSTAT [8]

The low productivity is mainly attributed to cultivation of largely the short day genotypes accompanied by inefficient production and protection management practices, poor post harvest management and unpredictable market situation. The long day type garlic is far more productive than short day type probably due to more availability of photosynthetically active radiation (PAR) as reported by [7]. The low productivity and yield in India is because main garlic supply comes from the states that are growing intermediate to short day type clones while most of the countries showing greatest production and productivity lie at higher latitudes and grow long day garlic. In India, there are small areas in the states of HP, J&K and Uttarakhand having long day conditions suitable for long day garlic cultivation where there is a great need for development of more long day garlic cultivars and to promote them over large area along with suitable production and post harvest package.

Garlic is a difficult crop in a sense that it imposes challenges like sterility, limited genetic variability, large genomic size and bolting, biotic and abiotic stresses like viruses, fungal and bacterial rots, pests, drought, and erratic temperature to the producer as well as the breeder. However, despite these natural obstacles, few studies have been conducted that led to the discovery of facultative apomicts, induction of sexual reproduction by manipulation of environment to enhance genetic variability and elucidate genetic/molecular understanding for crop improvement and control on bolting behavior. Despite the present problems, long day garlic holds promise for its productivity, quality, genetic and molecular understanding, and genetic improvement aided by biotechnological means and international commerce.

Status of garlic research in India and elsewhere

There are unique researchable aspects of garlic improvement in general and long day garlic in particular that pertain to Indian as well as world garlic research community. In order to provide for its ever increasing population, meet export and processing demands by the year 2050, India will have to produce 30 lakh tone of garlic [8]. The increase from present 12.5 lakh tone production will entail the need for genetic improvement via creation of variability, better plant protection measures, improved production technology, molecular understanding and explorations and introductions. The present scenario of attempts made in meeting these objectives in India and abroad and their scope in improving garlic genetics and productivity have been discussed below:

Indian garlic germplasm and cultivars

Due to apomictic nature of garlic, exploration and clonal selection have been the most widely implemented breeding strategies in India. The ICAR's Directorate of Onion and Garlic Research (DOGR), Rajgurunagar; ICAR institutes like Vivekananda Parvatiya Krishi Anusandhan (VPKAS), Almora, Central Institute of Temperate Horticulture (CITH), Srinagar; state university Mahatama Phule Krishi Vidyapeeth (MPKV), Rahuri and National Horticulture Research and Development Foundation (NHRDF), New Delhi have been instrumental in developing and identify clones suitable for different day length conditions of the country after rigorous evaluation through All India Network Research Project on Onion and Garlic (AINRPOG) and AICRP (Vegetable crops). The garlic varieties developed and/or released specifically for short, intermediate (Table 3) and long day conditions of India (Table 4) are enlisted below:

Table 3: The yield potential of some popular short and intermediate day garlic cultivars of India

S.no.	Cultivar	Yield (t/ha)	Source
1	Bhima Purple (SD)	6-7	DOGR, Pune
2	Bhima Omkar (SD)	8-14	DOGR, Pune
3	Agrifound White (SD)	12-14	NHRDF, New Delhi
4	Yamuna Safed (SD)	15-17	NHRDF, New Delhi
5	Phule Baswant (SD)	10-11	MPKV, Rahuri
6	Ooty-1 (ID)	15-17	TNAU, Coimbatore

SD: Short Day, ID: Intermediate Day

Table 4: The yield potential of long day garlic cultivars of India

S. no.	Cultivar	Yield (t/ha)	Source
1	VL Garlic-1	14-15	VPKAS, Almora
2	VL Lahsun-2	24-26	VPKAS, Almora
3	CITH-G-1	25-35	ICAR-CITH, Srinagar
4	CITH-G-3	25-28	ICAR-CITH, Srinagar
5	Mukteshwar-Sel-2	16-21	RS ICAR-CITH, Mukteshwar
6	Agrifound Parvati	17-18	NHRDF
7	Agrifound Parvati-2	17-22	NHRDF

(Recommended for states of Jammu and Kashmir, Himachal Pradesh, Uttarakhand and North Eastern States)

The ICAR-CITH, Srinagar has conducted several explorations in J&K and identified as many as 73 garlic clones from different areas of Kashmir on the basis of phenotypic variability and are being evaluated for higher resistance/tolerance to diseases and pests and yield parameters like polar and equatorial diameters, average bulb weight, number of cloves, average weight of ten cloves, total yield and marketable yield. These clones have considerably greater marketable yield potential compared to their short day and intermediate counterparts. The marketable yield during 2015-16 ranged from 6.6 t/ha to 44.15 t/ha with a mean of 23.70 t/ha. When compared with popular short and intermediate garlic clones grown elsewhere in India, these collections provide great promise in escalating India's productivity.

ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan, Almora has released two high yielding cultivars VL Garlic-1 and VL Lahsun-2. The ICAR's Directorate of Onion and Garlic Research, Rajgurunagar is also contributing to the long day germplasm collected from different parts of the country including states of Sikkim and West Bengal and abroad, which are being evaluated under long day conditions of Kashmir valley of which four lines are found promising for long day conditions with good horticultural traits and high yield.

Sterility

To meet the objective of exploiting genetic variability in garlic, there is prerequisite for its creation to start with. Garlic has very limited genetic variability because it is inherently apomictic. Although it is rather established that garlic is an obligate apomict, there have been speculations that it might be cross pollinating in the wild, given the great diversity found in garlic accessions around the world. Kamenetsky *et al* evaluated 115 accessions of garlic collected from Central Asia for bolting, umbel formation, pollen viability, stigma receptivity, embryo viability and seedling development [9]. Five accessions were found to fulfill all above criteria of being classified as fertile accessions for use in creating genetic variability and act as virus free garlic propagation material. In addition, sexually reproducing accessions that set true seed have also been developed but are mainly being used for research purpose as of yet [10, 11].

Most garlic accessions and commercial cultivars either don't flower or have sterile pistils and/or stamens or exhibit floral abortion. This restriction also necessitates the use of cloves as propagating material, which is cumbersome and cost intensive approach to garlic propagation and production. The various possible morphological, physiological, genetic, anatomical and molecular reasons of apomixes have been attributed to floral abnormalities [12], sterile hybridity from cross between two ancestral parents [13], competition of floral buds with vegetative topsets [14], tapetal degeneration [15], interference of degenerative like diseases with sexual reproduction [16, 17] etc. Although, many long day garlic clones bolt and bear flowers but they do not set seeds while short day garlic completely lacks flowering. The cloves (sometimes top-sets) as propagating material are susceptible to diseases and disorders (discoloring, sprouting, rooting, and rotting) and demand curing, storage space and maintenance till next planting time. Hence, it is need of the hour to look for ways to discover/ induce sexual reproduction in garlic. In this direction, some workers have been able to obtain fertile seed setters at least for research purpose through various means like explorations, selections, procedures on reproductive parts of long day accessions, studies on physiology of flowering, and manipulation of photoperiod [18, 19, 20, 21]. More explorations from Central Asia for collection of diverse garlic germplasm are required, as possibility of presence of accessions with facultative and obligate sexual reproduction in the centre of diversity (Central Asia) may open a window into the evolution of syngamous (sexually reproducing) garlic cultivars for commerce. This will greatly economize garlic production by decreasing storage losses and investment on storage and maintenance of planting material (cloves), simplifying the propagation and genetically ameliorating the crop.

In India, clonal selection has so far been a successful player in isolation of genetically superior accessions but no efforts have been directed towards discovery or induction of male fertile accessions. However, tissue culture technique for induction of somaclonal variations in garlic is being attempted at the ICAR-DOGR, Rajgurunagar. Along with molecular screening of garlic accessions for identifying bolting genes, work on exploitation of somaclonal variations may also be required in long day garlic for creation of variation for its further improvement. There are prospects that a somaclonal variant having potential to flower under natural conditions may be achieved. The markers linked with bolting behavior of garlic can be very beneficial in understanding the flowering habit of garlic and in developing fertile clones.

Limited genetic variability

Identified as obligatory apomict, garlic is considered to have very limited genetic variability. Owing to this, garlic is given the status of undomesticated crop despite its long history of cultivation, as humans have not been able to tap most of its genetic variation [22]. The vegetative nature of reproduction makes impossible the use of conventional methods of crop improvement. The absence of genetic variability limits the breeding of newer cultivars for high yield, better quality and pest resistance *via* hybridization or selection. At present, most of the genetic improvement in garlic through clonal selection has been achieved mainly in clove number, size and earliness [23]. However, with the induction and selection for male fertility using various techniques by workers in different parts of the world, opportunities are coming up for genetic recombination, genetic and molecular studies for garlic breeding as reviewed by [22]. For improving fertility trait and obtaining true seeds, selections for improved inflorescence traits are done. As a result, lines with inflorescence having reduced number of bulb-lets have been achieved, which might result in production of genetic stocks having no bulb-lets and complete pollen fertility in future [22]. In addition to this, some molecular markers have also been developed for marker assisted selection of male fertile plants before flowering [24, 25]. The validation and utilization of these markers in available germplasm for long day region can effectively assist in selection of male fertile plants for development of true seed setting lines/parents. These parents on inbreeding can act as genetic contributors to F_1 hybrids or as base material for further selections. Some workers have reported significant variability for important bulb and plant traits among garlic lines obtained *via* true seed [26, 27]. These results clearly demonstrate the rising success in obtaining genetic variability through sexual reproduction in garlic, whether through selection or explorations in its centre of diversity. These studied traits include bulb and clove weight, number of cloves per bulb, bulbing ability, bulb color and size, days to bulb maturity etc. an interspecific cross of garlic with *Allium ampeloprasum* (great headed garlic) has also been reported using fertile garlic accession and ovary culture [28]. In contrast to short day cultivars, the application of these breeding tools is much higher in long day garlic as they are naturally more pre-disposed to sexual reproduction.

Large genomic size

Garlic has the 32.7 pg DNA per 2C nucleus with low GC content and large amount of repetitive sequences. Among vegetable crops, this size is the largest, almost approaching that of onion. The large size and duplication are the major hindrances in developing biotechnological tools (like genomic libraries, molecular markers, diversity analysis, genetic fingerprinting), mapping and tagging of genes for assigning functions to the genes and other molecular studies. Locating the genes of interest has been compromised because development of genetic map requires genetic variability that arises from sexual reproduction only. Therefore, marker assisted selection in garlic has largely remained constrained for considerable time. Fortunately, with commencement of laboratory based sexual reproduction in garlic, few genetic maps have been developed in last decade although the density of markers including isozymes, RAPDs, AFLPs, and SSRs is low and only few gene specific markers have been mapped, for example, for male sterility, allinase, chitinase, CHS (Chalcone synthase) and SST (Somatostatin) [12, 13, 28]. In addition to their utilization in marker assisted selection, these genetic maps have revealed the nature of genome, extent of diversity and duplication in germplasm [29] and will give way to a full map for garlic in future. In context with Indian long day garlic, progress in understanding of genome may result in finding out the genes, which may help in breeding the garlic lines that are relatively resilient to climatic extremes, biotic stress, post harvest damage and better quality traits since the infrastructure for assuring such conditions is not very efficient in the country.

Diseases and pests

Garlic is highly susceptible to a wide range of viruses that include Onion Yellow Dwarf Virus (OYDV), Leek Yellow Stripe, Iris Yellow Spot Virus (IYSV), shallot latent viruses and Garlic mosaic viruses. Common fungal and bacterial diseases that pester garlic are Stemphylium leaf blight (*Stemphylium vesicarium*), downy mildew (*Peronospora destructor*), purple blotch (*Alternaria porri*), Fusarium basal plate rot (*Fusarium oxysporum* f. sp. *cepae*), white rot (*Sclerotium cepivorum*), Colletotrichum blight/anthracnose (*Colletotrichum gleosporoides*), black mould (*Aspergillus* sp.), bacterial soft rot (*Erwinia carotovora* and others), bacterial brown rot/slippery skin (*Pseudomonas aeruginosa*) and the major insect pests are onion thrips (*Thrips tabaci*) and onion maggots (*Delia antiqua*). However, the prevalence of viruses in long day conditions is lesser but it is nevertheless affected by Stemphylium leaf blight, downy mildew and occasionally purple botch with onion thrips being its major insect pest. With proper adoption of crop rotation, dibbling date, soil treatments and chemical control disease and pest incidence can be considerably reduced. However, intervention of advanced technology is required for cost effective control on biotic stress borne by garlic. Till date significant laboratory success has been achieved in elimination of viruses and pests by tissue culture techniques like meristem culture, somaclonal variations, and thermotherapy. Proper utilization of resistant or clean end products from these experiments will be helpful in developing virus free/resistant cultivars in future [30, 31, 32, 33]. Recently, Indian workers have succeeded in characterizing and analyzing candidate gene linked to *Fusarium* basal plate rot disease. The study will help in developing molecular markers linked to this disease and help screening resistant plants/cultivars at seedling stage [34]. ICAR-DOGR, Rajgurunagar has developed commercial rapid detection RT-PCR kits for Iris Yellow Spot Virus and Onion Yellow Dwarf Virus useful for rapid and high through put detection of diseases in garlic crop samples. Few reports on discovery of new viruses (Leek Yellow Stripe Virus) infecting garlic in India have also been reported [35, 36].

Post harvest abiotic stresses

For long term storage (about 9 months) of garlic, the optimum temperature falls between 0 and -1 ºC and 60-70% humidity (Medina and Garcia 2007). This environment can't be maintained at ambient weather of garlic producing regions. The temperate regions experience temperatures and relative humidity far beyond these values during the period between harvesting and next planting. The bulb sprouting may occur at temperature from 5-18 °C. Temperature in this range easily occurs and stays during the storage period of garlic in temperate regions. This challenge necessitates the controlled environment storage facilities and logistics and abiotic stress resistance breeding. The greater resilience to temperature and humidity extremes will not only reduce post-harvest damages but also extend long day garlic sale in neighboring states, raise opportunity for storage till the period of greatest demand and comply by the shipping requirements for export consignments. Though the breeding attempts at improving post harvest life of garlic have not been reported, NHRDF and ICAR-DOGR have recommended post harvest practices for curing, grading, packaging and storage of garlic under Indian climatic conditions. The schemes for technical support in the form of minimally as well as fully controlled environment facilities, credit by state horticulture departments will also favor the processing of garlic into various value added products (powder, paste, oil, oil macerate, extract, roasted, frozen etc). Such incentives may raise farmers' interest in large scale cultivation of garlic, thereby, providing employment opportunities to youth and women, improving gender equity in the region and boosting India's garlic production.

Conclusion

In spite of many constraints in achieving world level production and productivity of garlic in India, research is underway to resolve the current issues and assure India's better position in domestic and international market. Currently, most success in achieving genetic improvement in long day garlic has been through clonal selection but standardization of biotechnological tools to induce variations is afoot. Few syngamous accessions have been developed to carry out genomic and interspecific gene introgression studies. Genetic linkage maps have begun to be developed with few important loci placed on approximate locations of the genome. Molecular markers like SSR, RAPD have been developed for diversity studies. Virus indexing and molecular studies for locating and characterizing resistance genes have also been initiated. If results of research are systematically interpreted and applied in garlic breeding, multiplication, production, storage and processing, garlic can become highly remunerative, and more so to the farmers of Indian Himalayan Region, which is natural habitat to highly productive long day garlic.

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