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REVIEW

# Garlic: retrospect, status quo and dimensions

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**Abstract** 'Garlic' (*Allium sativum* L.) is the second most important cultivated *Allium* known throughout the world. It is known for its versatile use as a spice, condiment, vegetable and an intended medicinal panacea. Its clove contains sulphur-based compound 'Alliin' (S-allyl-L-cysteine sulfoxide) predominantly as an active ingredient, which on physical injury to the clove becomes 'Allicin'. Alliin and allicin both are devoid of lachrymatory factor so, it does not make one tears-up while chopping garlic cloves. Origin, history, phylogeny, different types with classification, propagation, bulbils, flowering potential, studies with fertile clones, germplasm, improvement efforts along with the worth knowing well-researched facts about garlic are consolidated in the present paper. This review aims to convey an amalgamated overview of garlic and necessarily provides a retrospect of garlic's past to have a rear-view and helps to understand the status quo from the research standpoint further. It is an attempt to speculate garlic's research dimensions.

**Keywords** Garlic · *Allium sativum* · Germplasm · Bulbils · Flowering · Electron beam

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## Introduction

Garlic is an immensely important cultivated *Allium* across the globe which contains predominantly colourless, odourless and water-soluble, sulphur-based compound 'Alliin' (S-allyl-L-cysteine sulfoxide) (Block et al. 1980; Ohsumi et al. 1993) which on physical injury to the clove gets converted into 'Allicin'. 'Alliin' or 'Allicin' both are devoid of lachrymatory factor so, it does not make one tear up while chopping garlic cloves, unlike an onion. Valued both as a spice and condiment, raw garlic cloves taste pungent but mellow when cooked whereas rich and nutty when roasted and caramelized (Perry 2004), it is being utilized in the preparation of different vegetarian and non-vegetarian cuisines. Garlic paste, dehydrated powder is available in the market, moreover, not limited just for seasoning; it is an ingredient for preparing food products viz., chutneys, pickles, etc. Sara Perry dedicated a complete book with photographs by France Ruffenach to underline the multifaceted uses of ingredient garlic through more than sixty-five recipes (Perry 2004) and made believe its

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readers 'everything tastes better with garlic'. A peeled fresh-garlic clove along with carbohydrates, moisture, protein, fat, fibre, mineral matter, contains Vitamin C and Vitamin B (Pruthi 1979). The nutritional composition with ORAC (Oxygen radical absorbance capacity) values of 1 g raw garlic clove (Table 1) was released by USDA for standard reference in their Nutritional Database (Charles 2012). However, chemical composition and bioactive compounds content in garlic are highly dependent on pre-harvest and also on post-harvest conditions; special emphasis on the cultivation practices, genotype selection and growing conditions must be laid for harvesting the maximum quality (Martins et al. 2016).

Besides cloves, green scapes and garlic leaves are also consumed as fresh or cooked (Jo et al. 2012) in South China and South Asia special clones have been selected for leaf production (Etoh and Simon 2002).

Garlic's therapeutic uses have an origin in antiquity reflected through archaeological records from ancient Egypt, India, Greece, Rome, China and many cultures (Suru and Ugwu 2016) therefore, intended as a medicinal or nature's panacea (Ankri and Mirelman 1999; Suvarna and Rajagopalan 2015). 'Alliin' is the precursor of 'Allicin'; on crushing the garlic bulb, the enzyme alliinase breaks down alliin to produce 'allicin' an allyl thiosulfinate (Sterling et al. 2001). Allicin has antifungal properties (Cavallito and Bailey 1944; Ohsumi et al. 1993) and a number of plant fungi had shown toxicity for garlic juice (Pordesimo and Ilag 1976). Allicin also exhibited antibacterial activity against a wide range of gram-negative and gram-positive bacteria along with antiparasitic activity for some major human intestinal protozoan parasites. Besides, a wide range of human infecting viruses had shown sensitivity to crushed garlic preparations (Ankri and Mirelman 1999). Garlic extract is a natural blood thinner and has a hypocholesterolemic action (Augusti 1977), thus, aptly used as a traditional medicine for the prevention and treatment of cardiovascular disease (Ackermann et al. 2001).

**Table 1** Nutrient composition and ORAC (Oxygen Radical Absorbance Capacity) values of garlic raw 1 clove (1 g)

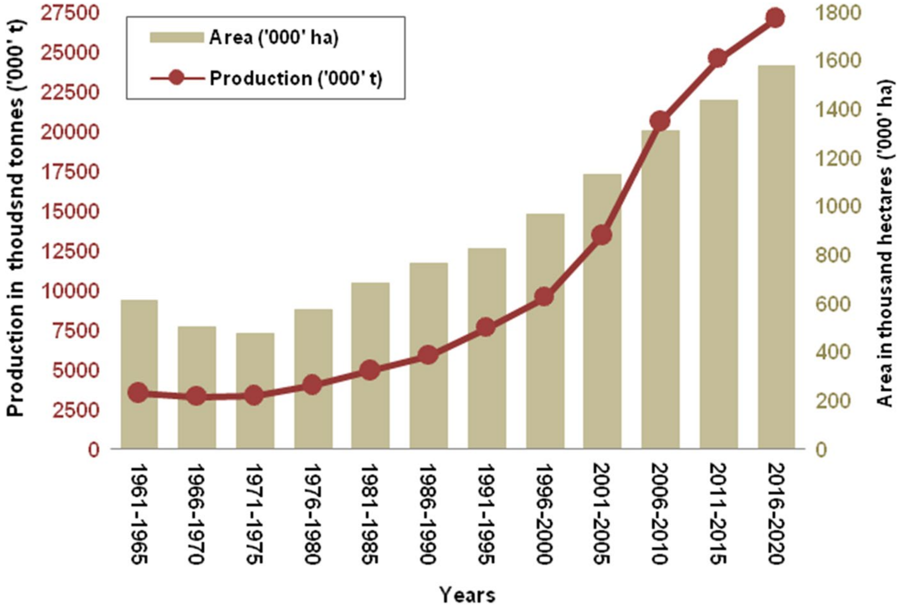
| Nutrient | Units | Value per 1 g (1 clove) |
|---|---|---|
| Water | g | 58.58 |
| Energy | kcal | 149 |
| Protein | g | 6.36 |
| Total lipid (fat) | g | 0.50 |
| Ash | g | 1.50 |
| Carbohydrate, by difference | g | 33.06 |
| Fiber, total dietary | g | 2.1 |
| Sugars, total | g | 1.00 |
| Calcium, Ca | mg | 181 |
| Vitamin C, total ascorbic acid | mg | 31.2 |
| Vitamin B-6 | mg | 1.235 |
| Vitamin A | IU | 9 |
| Vitamin E (alpha-tocopherol) | mg | 0.08 |
| H-ORAC | µmol TE/100 g | 5.541 |
| L-ORAC | µmol TE/100 g | 400 |
| Total-ORAC | µmol TE/100 g | 5.708 |
| TP | mg GAE/100 g | 92 |

*Source*: USDA National Nutrient Database for Standard Reference

Garlic has been therefore admired as the second most important *Allium* known throughout the world; is a status it still holds. To one surprise, 'garlic tea' is also relished by many and ready to brew garlic tea bags are also available in the market. Additionally, in few parts viz., USA, UK, Canada, food festivals (https://gilroygarlicfestival.com; www.garlicfestival.co.uk; www.torontogarlicfestival.ca) are being organized yearly as an event under the name of Garlic for its foodies and connoisseurs.

China, India and the Republic of Korea are the top three world garlic producers, whereas Asia alone contributes more than 85% to the world garlic production. From 1961 to 2020, the global average production of garlic has exhibited an increasing trend with the increasing global area (Fig. 1), discounting hardly the exceptional lustrum 1971–1975 wherein the global area decreased compared to its previous lustrum without downfall in the yield. The most recent available comprehensive garlic data of the year 2020 shows that the garlic harvested from 1.63 Million ha provided 28.05 Million tonnes of bulb production exhibiting 17.19 tonnes/ ha as the world's average garlic productivity (FAO 2022). The incremental trend of the area under garlic and production witnessed from the past; highlights the crucial demand and so the importance of this crop. In line with the increasing trend of population, to cater to the requirement of garlic in the future demands productivity augmentation. It is imperative, therefore to have a consolidated context of past efforts in garlic, the *status quo* from

**Fig. 1** Lustrum-wise average global area and production of Garlic




a research standpoint and to speculate its dimensions and means for future garlic research.

## Retrospect

### Origin and history

Linnaeus (1753) and Don (1832) proposed that 'Garlic' (*Allium sativum*) originated in the Mediterranean basin. Vavilov (1951) and Kazakova (1971) underlined that Central Asia is the primary centre of origin of *A. sativum*, with the Mediterranean basin or the Mediterranean and the Caucasus as secondary centres. Most recently, the area of Tien-Shan Mountains is regarded by Etoh (1986), as the centre of origin of garlic and the Caucasus to be the secondary centre of origin (Etoh and Simon 2002). One of the reasons, why the centre of the origin is unclear; is the unknown progenitor species of cultivated garlic. Wild species *A. longicuspis* Regel, was considered by taxonomists as the ancestor of the domesticated garlic (Regel 1875). However, based on the isozyme and RAPD profiles (Pooler and Simon 1993; Hong 1999; Ipek et al. 2003) modern taxonomists suggest that garlic and *A. longicuspis* form a species complex (Maaß and Klaas 1995; Fritsch and Friesen 2002). A truly wild ancestor, the wild species of *A. sativum* is still unknown (Fritsch and Friesen 2002) and, hitherto, could not be traced by researchers.

De candolle (1886) contemplated that garlic from its original home spread to the other parts around 2000–1500 BC, before the migration of Aryans. Engeland (1991) produced a historical map by exploring the garlic history and indicated that wild garlic might have been much dispersed in early times and that it could have been taken by nomadic tribes to southern villagers; further, the spread might have continued to the Mediterranean basin and India. He also quantified that garlic was introduced to India more than 5000 years ago. Garlic from India spread further to the east, maybe to South-East Asia (Burkill 1966). The Caucasus is a natural bridge of garlic dissemination to the north into Russia, Ukraine and Eastern Europe, along with in the south to the shores of the Mediterranean or south-west through Turkey to south-eastern Europe. Garlic was introduced into sub-Saharan Africa and to the Americas with explorers and colonists from the Mediterranean region (Etoh and Simon 2002). Garlic was introduced into Japan from Korea, whereas it was introduced into China most likely from Central Asia by the wandering traders and the Chinese name for garlic probably, therefore, connotes its western Chinese origin (Etoh and Simon 2002).

## Morphology and phylogeny

The anatomy of garlic was described by many researchers (Mann 1952; De Mason 1990; Takagi 1990). A normal garlic bulb is composed of multiple cloves (aggregate bulb) that actually born at the base of leafy sheaths as axillary buds. By the time of harvesting maturity, the cloves become fleshy storing foods and the main stem and leaves get senescence. The garlic bulb then consists of dry leaf sheathes that covers the axillary cloves and matures. The mature bulb/cloves enter the dormancy stage which breaks over a period by producing the first characteristic flat leaf from the top of the clove while in the storage. A detailed account of garlic botany and morphology has been described in a chapter by Kamenetsky (2007).

Formerly, based on its superior ovary (of onion flowers), the genus *Allium* was a part of the Liliaceae family for a long time. Later, it was featured as a member of Amaryllidaceae in accordance with its typical inflorescence structure (flowers are born in a bracted umbel on top of the scape). In the latest classification, genus *Allium* is recognized as a distinct family of 'mostly bulbous or rhizomatous, perennial or biennial, geophytes with characteristic leaves, smell and umbellate scapose inflorescence which holds bisexual flowers having superior ovary thus, grouped under family "Alliaceae" (Heywood et al. 2007; Peter and Pradeepkumar 2008). The taxonomic hierarchy for garlic is, Class—Liliopsida; Subclass—Liliidae; Superorder—Liliianae; Order—Amaryllidales; Family—Alliaceae; Subfamily—Allioideae; Tribe—Allieae; Genus—*Allium* (Takhtajan 1997) and Species—*Allium sativum*.

Alliaceae is a monocot family to which garlic (*Allium sativum*) belongs. In spite of the fact that wild ancestor, wild species of *A. sativum* are unknown and all the cultivated garlic varieties till date are sexually sterile; it exhibits extensive variations in genotypes for maturity duration, pungency, flavour, bulb parameters, ability to produce scapes, number and size of cloves, top sets as well as flowers in the inflorescence (McCollum 1976; Astley 1990; Hong et al. 2000; Kamenetsky et al. 2007). Such a wide genetic variation in garlic is perhaps due to mutations (Burba 1993) and /or somaclonal variation (Novak 1990), and subsequent clonal selection under different eco-geographical conditions (Jones and Mann 1963; Rubatzky and Yamaguchi 1997). The genotypic and environmental, constructively strong interaction led, therefore, to a variety of phenotypic expressions (Lallemand et al. 1997; Portela 2001; Kamenetsky et al. 2007).

## Classification

The classification of different garlic genotypes as per distinctness remained a quite debated issue. On the basis of the development of 'scape', which forms a characteristic 'scape-wood' in the bulb centre and around which the cloves are arranged, garlic is considered as Hard-neck otherwise classified as a soft-neck (Fig. 2). To further fine-tune, based on the ability to produce a scape, garlic genotypes had been simply subdivided into two distinct sub-group as bolters and non-bolters, which were furthermore categorized into complete bolters, incomplete bolters (semi-bolters), non-bolters (Fig. 2).

Garlic grouping depended on the requirement of the day length for its bulb production are known to most as Long-day and Short-day types. The bulb skin colour also splits garlic into two types viz., white bulb and purple or purple stripe type. Big clove and Small clove garlic whereas multi-clove and single clove garlic are on the other hand roughly carved separations dependent on bulb size and the number of cloves it holds in a bulb (Shinde et al. 2003; Kamenetsky et al. 2004; Meredith and Drucker 2018). However, the 'Single clove or elephant garlic' although regarded as garlic is actually '*Allium ampeloprasum* var. *ampeloprasum'* which gives purple-flowered umbel (Fig. 3.).

Helm (1956) described three botanical varieties of *Allium sativum,* viz., var. sativum, var. ophioscordon and var. pekinense. In 1963, Jones and Mann recognized two distinct botanical varieties of garlic viz., ophioscorodon and sativum. Engeland (1991, 1995) proposed that the garlic taxon consist of the two subspecies *ophioscorodon* and *sativum* (Table 2), may be better regarded as subgroups (Etoh and Simon 2002). The subsp. *ophioscorodon* usually develops flower stalks, and includes two varieties, 'Rocambole' and 'Continental. Further, 'Continental' variety was divided into two varieties, 'Purple Stripe (including marble purple stripes)' and 'Porcelain'. 'Rocambole' has distinctively coiled (1–3 coils) flower stalks with numerous, very tiny topsets (Etoh and Simon 2002). Helm (1956) studied rocambole, and concluded that

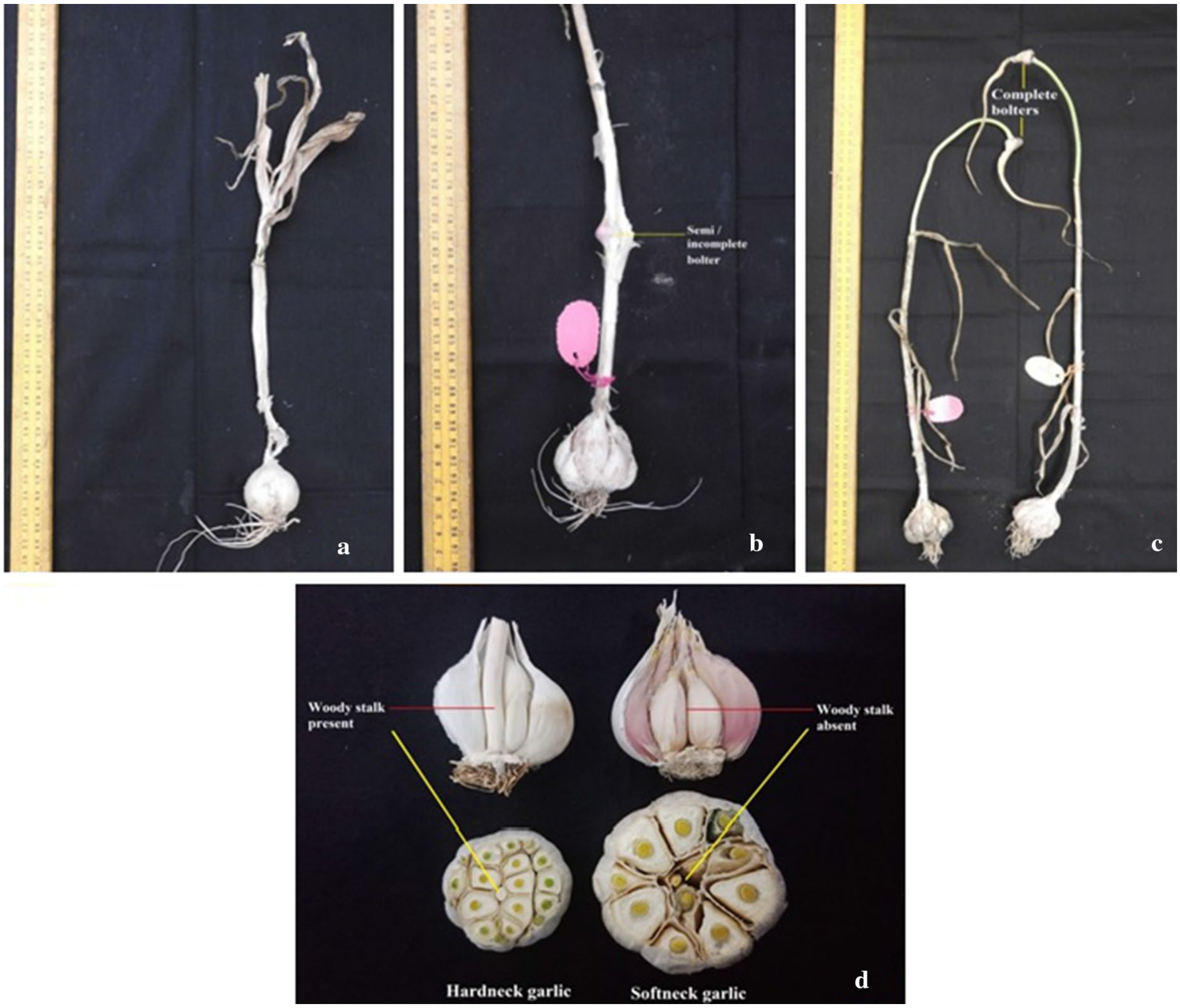



**Fig. 2** *Allium sativum* **a**. Bolter **b**. Semi-bolter **c**. Complete bolter **d**. Hardneck and softneck types

**Fig. 3** *Allium ampelorasum* var. *ampelorasum*

**a** Bulb - *Allium ampeloprasum* var. *ampeloprasum* **b** Umbel - *Allium ampeloprasum* var. *ampeloprasum*

**Table 2** Phenotypic classification

| *Allium sativum* sub-species/group | Variety/type | No. of cloves per bulb | Reference |
|---|---|---|---|
| *Allium sativum* ssp. *ophioscorodon* (Hardneck types: Usually develops flower stalks) | Rocambole (1–3 coils flower stalks) | 3–14 | Engeland (1991, 1995) |
| | Continental-Purple Stripe (including marble purple stripes) | 8–12 (4–7, for marble purple strips) | |
| | Continental- Porcelain* | 2–5 | |
| *Allium sativum* ssp *sativum* (Softneck types: often develops no flower stalk, if bolts at all, produces a weak flower stalk) | Artichoke (It sets bulbils in the false stem, produces early maturing bulbs) | 12–16 | Engeland (1991, 1995) |
| | Silverskin (Produces late maturing bulbs) | 8–24 | |
| | Asiatic* (Produces drooping scapes) | 4–8 | Engeland (1991, 1995; Pooler and Simon 1993) |
| | Creole (Possess tallish cloves with elongated tips) | 4–8 | |
| | Turban (Produces turban shaped scape head) | 7–11 | |

*Volk et al. (2004)[a] mentioned Continental-Purple Stripe and Asiatic type corresponding to *longicuspis* and *peckinse*

this name should only be applied to forms of garlic with coiled scapes, and not to *A. scorodoprasum*.

The subsp. *sativum* develops no flower stalk, if it bolts at all, produces a weak flower stalk, and it includes two types; ‘Artichoke’ and ‘Silverskin’ (Engeland 1995). ‘Silverskin’ rarely develops topsets, and produces only late-maturing bulbs (Etoh and Simon 2002). ‘Artichoke’ frequently has sets (bulbils) in the false stems (incomplete bolting type) and early-maturing bulbs. Soft-neck cultivars often grow best under mild winter conditions (Engeland 1991, 1995) compared to the Hard-neck once.

Pooler and Simon (1993) grouped ‘Asiatic’, ‘Creole’ and ‘Turban’ types under softneck; however, classification of these garlic types are in the doldrums. ‘Asiatic’ types occasionally produce drooping scapes, ‘Turban’ types are similar to Asiatic types but bears a turban shaped scape head. ‘Creole’ types possess tallish cloves with elongated tips (Engeland 1991, 1995). Characterization of garlic has predominantly been based on phenotypic evaluation; but, agro-climate can affect morphological characters. Therefore, it complicates the characterization of garlic clones (Bradley et al. 1996; Al-Zahim et al. 1997).

Some investigators have targeted evaluation of garlic diversity and considered morphological traits along with molecular markers viz., isozymes and DNA (Pooler and Simon 1993; Etoh et al. 2001; Lampasona et al. 2003; Zhao et al. 2011; Jo et al. 2012). Further, Maaß and Klass (1995) based on morphological and isozyme variations, grouped garlic species into *longicuspis group*: covering most garlic clones from Central Asia; *subtropical group*: which developed under the climatic conditions of South-east and East Asia; *ophioscorodon group*: which is derived from Eastern Europe; and the *sativum group*: from the Mediterranean. On the other hand, according to Fritsch and Friesen (2002), the above-mentioned groups viz., *Longicuspis*, *Ophioscorodon*, *Sativum* along with two subgroups viz. *Subtropical* and *Pekinense*, form a complete *Allium sativum* species complex. Phenotypic, isozyme, along with other molecular markers are still being further researched for the refined garlic classification by garlic researchers from different parts of the world. After all, welcoming the reconstruction for verity has always been a part of science.

## Status quo

### Propagation, breeding and potentiality

*A. sativum* cultivars have a somatic chromosome number $2n = 16$ with a karyotypic formula of six metacentric chromosomes, four submetacentric chromosomes, and six acrocentric chromosomes (Jo et al. 2012) and its genome size is estimated at 15.9 Gbp, which is 32 folds larger than the rice genome (Shemesh-Mayer et al. 2015) and thus, obvious to infer that full sequencing of the garlic genome remains a challenging task (Kamenetsky et al. 2015).

Unusually, garlic was continued to consider as a sexually sterile and its sterility barred the enhancement of garlic genetic potency through cross-hybridization (Lampasona et al. 2003). Garlic propagates clonally; hence, commercially ‘cloves’ are being used as a vegetative means of propagation. Clonal selection, therefore, was the only feasible breeding method to use the available natural variation and another one to the possible extent was exploitation using induced heritable mutations.

In vitro garlic propagation protocols facilitating high multiplication rate with the production of virus-free plants detailed by several researchers (Nagakubo et al. 1993; Seabrook 1994; Mohamed-Yassen et al. 1995; Haque et al. 1997; Myers and Simon 1998; Robledo-Paz et al. 2000; Ebi and Masuda 2000; Kim et al. 2003; Luciani et al. 2006). However, the use of tissue-cultured plantlets to field continues to face hindrance in its commercialization. One of the main reasons is, it takes 4 years (including successive clonal propagation cycles) to garlic tissue cultured plantlet for its fullest expression if apical meristem is used as an explant (Metwally et al. 2012). In abstract, there is much to be studied about efficient micropropagation in garlic, which if standardized, will make possible in vitro multiplication of garlic planting material on the one hand and on the other hand the bulbs bound to be used as a planting material can be channelled as marketable produce. The role of agronomical interventions in order to supplement the in vitro produced plantlets for their fullest exploitation should not be underestimated.

Bulbils/ aerial bulbs/ top sets are tiny structures that resemble cloves with relatively thin papery skin and bears on the scape of garlic (Fig. 4). They are also consumed similar to cloves and taste a bit pungent than their underground bulb due to its different environmental exposure. Bulbils are often seen when long day garlic genotypes are grown under the long-day conditions; their numbers vary from a few to more than 100/scape/plant depending upon various factors and they can be used as a vegetative multiplication mean (Fig. 4) for garlic (Kajimura et al. 2000; Stairs 2005; Meredith and Drucker 2018; Hedau and Chaudhari 2019).

Interestingly, garlic commercial cultivars do not produce true seeds being regarded as a sexually sterile diploid for long; in 1875, Eduard Regel described unique flowering characteristics in garlic found in the wild (Meredith and Drucker 2018). Notably, the Japanese researcher Prof. Takeomi Etoh, in the early 1980s, through several expeditions to Soviet Central Asia unearthed a number of garlic bulbs. Furthermore, the collected clones were grown in Kagoshima, Japan, and astound with the 17 clones, which developed fertile flowers with over 3,000 viable true seeds (seed germination rates were low, ranging between 10 and 12%) following the topset removal. Subsequently, in the 1990s, Maria Jenderek obtained in California a large amount of garlic true seeds from the plants originated in Central Asia (Etoh 1986; Kamenetsky 2018).

## From sterility to true seeds and interspecific hybrids

The root cause for sterility in the present cultivated garlic varieties as per acceptable hypothesis is, “During the garlic cultivation history, in order to obtain bigger bulb, flower scapes were repeatedly removed or clones with low flowering potentiality were chosen. This active selection by human for the thousands of years resulted in the loss of garlic fertility, and today the cultivated garlic varieties are completely sterile” to recapitulate, “the garlic evolution began with sexually reproduced plants, continued with sterility and incomplete bolting and reached at the non-bolting genotypes” ( Etoh and Simon 2002).

Koul and Gohil (1970) mentioned that while inflorescence development, bulbils and flowers compete for nutritional resources and bulbils win flowers while competing for nutrients (Meredith and Drucker 2018). Therefore, bulbil in the garlic inflorescence is considered as one of the causes of sterility (Kamenetsky et al. 2005).

In the past, because of garlic’s projected sterility and thereby acceptance of the precluded sexual path had factually lowered exploitation of its economically important traits. Kotlinska et al. (1991) collected a number of fertile clones of a primitive garlic type from the north-western side of the Tien-Shan Mountains in Central Asia, similarly, Etoh et al. (1992)

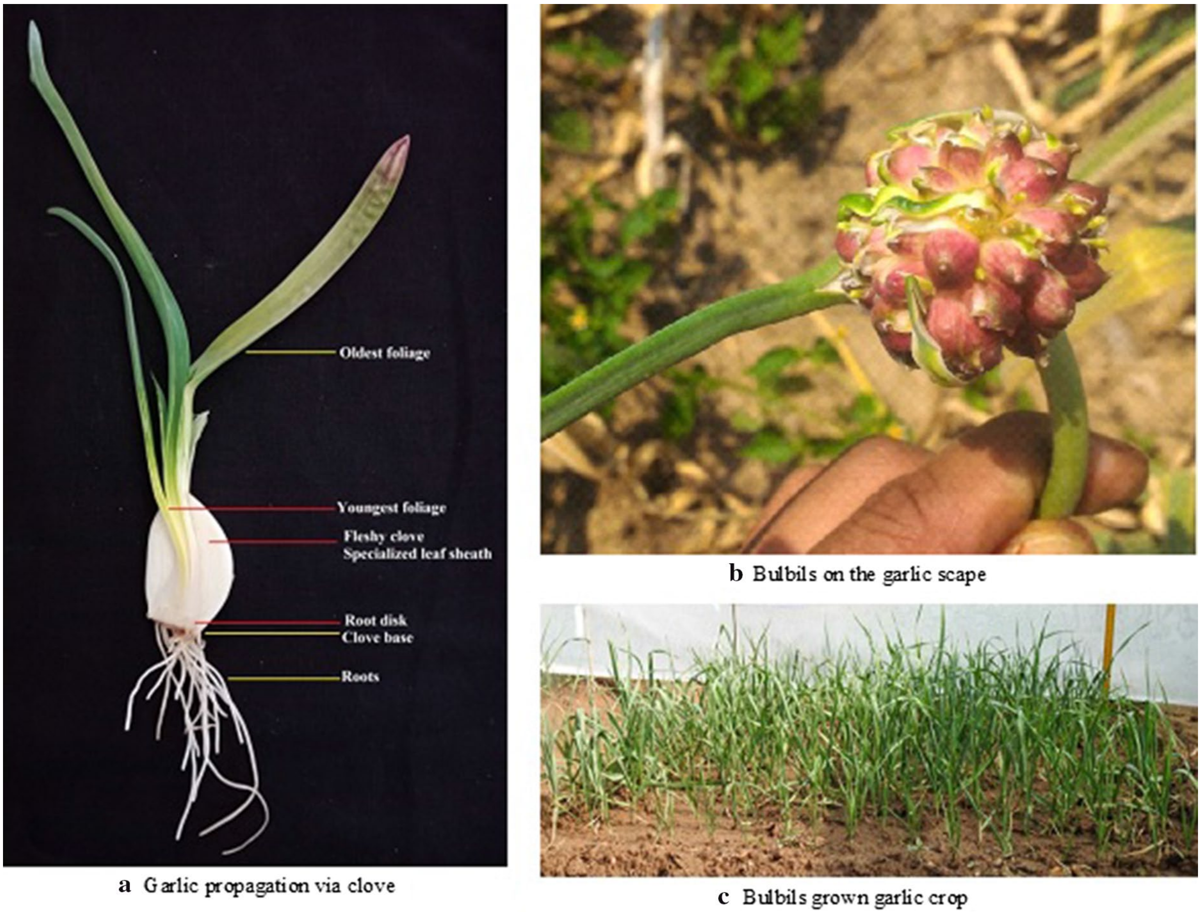



**Fig. 4** Gralic propagation using clove and bulbils

found few fertile clones in Caucasus (near the border with Turkey).

More recently, 36 fertile accessions were identified in two USA public garlic collections (Jenderek and Hannan 2000). Kamenetsky and Rabinowitch during the collection missions to Central Asia found the seven most fertile garlic accessions and when evaluated in Israel about 400—500 true seeds per umbel were harvested by them without the removal of top sets. Those seeds reached about 90% germination rate, and the seedlings developed into two to five leaves plants. Thereby, ultimately, single clove bulbs with differing in bulbing and skins colours were obtained (Kamenetsky 2018).

Just after the revelation of garlic potency to produce fertile pollen and true seeds had led the path towards the interspecific cross between *A. longicuspis* and *A. sativum* (Etoh 1984) wherein sterile *A. longicuspis* flowers pollinated with pollen from fertile garlic. The resulting hybrid, however, found sterile. The two species, *A. ampeloprasum* (as female) of leek group with fertile *A. sativum* belong to the *Allium sp.* although do possess different ploidy levels. Leek is a tetraploid (32 chromosomes), while garlic is a diploid (16 chromosomes), thus, interspecific triploids aneuploids were reported as recovered (Sugimoto et al. 1991). Ohsumi et al. (1993) secured hybrids between onion (*A. cepa*) and garlic (*A. sativum*) through conventional crossing coupled with embryo rescue. An interesting achievement, however, the hybrid plants reported merely 2% pollen viability and failed to produce seeds. Sterility is not at all astounding in this case since it was a very wide cross.

Certainly, well-represented garlic germplasm secured at different active germplasm sites, accessions in gene banks across the world and germplasm those are reported by researchers for their true seed producibility, will make possible, the expansion of the genetic variability for the economic traits subject to fertility restoration and its further use in the breeding for garlic improvement.

## Dimensions

### Germplasm

Considerable efforts are being made by different Institutes/ Gene bank/ Organizations (Table 3) for conserving the available garlic diversity, its maintenance, evaluation and to make available excellent garlic collections to researchers across the world. Genetic variability conservation demands maintenance, frequent accession regeneration and so it is an expensive and labour-intensive task. In vitro conservation of clonally propagated plants ensures the maintenance and enables conservation of planting material under a stable environment that can be regenerated at any time. Cryopreservation procedures are being implemented at the USDA-ARS National Center for genetic resources preservation (Volk et al. 2004b; Ellis et al. 2006). Conversely, In vitro, slow growth conservation has become a tool of conserving garlic germplasm with vigour, true to type condition and disease-free stage with low virus load (Hassan et al. 2007) and moreover it has been documented being economic than the In situ and cryopreservation (George 1993) method of germplasm conservation. Although the diversity has been nicely captured through collections, gaps exist. It is therefore of immense value to build the collections more inclusive by intensive explorations to the central Asian region for enriching the collection set with rare precious alleles to broaden the gene pool.

Biodiversity International (IPGRI 2001) has developed taxonomic keys in the descriptor of *Allium,* to classify garlic genotypes. Advisable and researched characterization studies have also been conducted in different parts of the world (Pooler and Simon 1993; Zhao et al. 2011; Lampasona et al. 2012; Hirata et al. 2016; Meredith and Drucker 2018) thereby revealing genetic variations for horticultural traits in garlic collections.

However, accessions reported generally have been hardly utilized further. Need is to remove the duplicates in the garlic collections to have a ‘core collection’ of a succinct size which could represent the complete genetic spectrum of the base collection. Briefly, a core collection should include a maximum of the genetic variation contained in the whole collection with minimal repetitiveness, ideally conserving at least 70% of the alleles in the whole collection (Brown 1989). The core collection set then should be evaluated for their trait-specific identification across environmentally varied locations.

**Table 3** Garlic germplasm: Gene bank/ Institute/Organization

| Sr. No | Institute/Gene bank/ Organization | Web-link/References |
|---|---|---|
| 1 | Leibniz Institute of Plant Genetics and Crop Plant Research (IPK) Gatersleben, Germany | https://gbis.ipk-gatersleben.de/gbis2i/faces/index.jsf |
| 2 | Nordic Gene Bank (today Nordic Genetic Resource Center, NordGen). Alnarp, Sweden | https://sesto.nordgen.org/sesto/index.php?thm=sesto |
| 3 | ICAR-NBPGR, New Delhi, India | http://pgrportal.nbpgr.ernet.in/(S(tjhxhbu43nrsc245yk12cf45))/AdvancePlantSearch.aspx?crop=garlic |
| 4 | ICAR-DOGR, Pune, India | http://www.dogr.res.in |
| 5 | INRA-Montfavet, France | https://www.bioversityinternational.org/fileadmin/user_upload/online_library/publications/pdfs/824.pdf |
| 6 | The Hebrew University of Jerusalem, Rehovot, Israel | |
| 7 | Plant Genetic Resources Laboratory, Research Institute of Vegetable Crops (RIVC), Skierniewice, Poland | |
| 8 | USDA Gemplasm, USA | https://www.ars-grin.gov/npgs/index.html |
| 9 | Kagoshima University, Japan | Hirata et al. (2016) |

Improvement strategies

The clonal selection remained a principal method for garlic varietal improvement across all garlic growing areas of the world. Below discussed are some other improvement strategies,

*Mutagenesis*

Variations due to mutations that accumulated over time were found; therefore, without an opportunity for inter pollination and/or sexual reproduction, new genotypes had been obtained through the selection of spontaneous mutations expressing traits of horticultural interest (Volk et al. 2004a). Physical mutagens like gamma rays, X-rays and chemical mutagens like EMS are although studied by many researchers; the recovery of horticultural desirable mutants still remained an area to explore further. The sensitivity to different mutagenic agents differs based on genotypes and the stage at which the material is being used for inducing mutation. A garlic leaf explants generated callus exposed to gamma irradiation studied by Mostafa et al. (2015) for mutation induction in garlic. A detailed account of various detection techniques for somaclonal variation; broadly categorized as morphological, physiological/biochemical and molecular, provided by Bairu et al. (2011). Al-Zahim et al. (1999) described the somaclonal variation in garlic as well as the detection of the same using RAPD and cytological analysis. The clove prorogation is the only commercially acclaimed method of garlic multiplication till date; therefore, clonally heritable induced mutations are still an area to focus on. The use of electron beam technique and standardization of dose for garlic mutagenesis can help for basic mutagenic studies and it may help for recovery of desirable mutants to use as new garlic cultivars as in groundnut by Mondal et al. (2017) and in black gram by Jegadeesan et al. (2016).

*Hybridization*

The early efforts made by researchers described some fundamental aspects related to garlic true seed. Most recently, a detailed account of garlic true seeds mentioned by Meredith and Drucker (2018), and they affirm that garlic flowers are protandrous, alike onion flowers. The individual garlic flowers are incapable of self-pollination because the anthers burst, releasing pollen two to four days before the stigma of the same flower becomes receptive i.e. protandrous. An inflorescence of a garlic plant blooms over five to twenty-five days. Therefore, although individual flowers are incapable of self-pollination, the other flowers from the same inflorescence / umbel can provide pollen grains to fertilize remaining receptive flowers. Garlic flowers are typically entomophilous (honeybees, houseflies accomplish pollination). Each garlic flower ovary is trilocular and each chamber contains two ovules; therefore, it has a ceiling of six seeds per individual flower. Similar to the case of onion, ovaries swell as the seeds develop; matured seeds are ready for harvesting roughly two months after pollination. Garlic seed is a bit smaller comparatively but mimics onion seed. Garlic true seed has a dormancy period and freshly harvested seeds should not be planted immediately. A seed planted crop produces a round bulb (a bulb that is undivided into separate cloves) in the first year. The same round bulb planted next time develops a normal bulb. The newly harvested garlic bulbs, including round bulbs, also exhibit a natural period of dormancy. A possibility which was shared by researchers seems thought-worthy here "In future, we may produce on large scale the garlic bulbs using its seeds (Kamenetsky 2018; Meredith and Drucker 2018) like we produce onions".

As an extract inference; the ability to produce true seed and thereby possible crossing between fertile garlic genotypes (Etoh 1986; Etoh et al. 1992; Jenderek and Hannan 2000; Kamenetsky 2018) would bring great benefits in terms of variability creation and ultimately it will add to the field of garlic improvement. Additionally, propagation of desired genotypes via true seeds would be expected to result in reduced storage expenses and restricted injuries by diseases and pests transmitted by infected vegetative propagules. The study in the area of fertility restoration and sexual reproduction in garlic would permit genetic studies and greatly help endeavours in the classical breeding of garlic. The past attempts made with fertile garlic related to interspecific hybridization for the possibility of creating variation and for the genetic studies can be reinvestigated with supplementation of the advancements made in different in vitro propagation techniques.

Nature's wonder: Garlic Bulbils/ Aerial bulbs/ top sets

Garlic is usually propagated using cloves. This demands holding-back of the commercial produce, every year, as high as almost 10 per cent of its per hectare yield for growing the immediate next crop, particularly of Long Day garlic. This is the major reason for the limited area under cultivation of Long day garlic. Bulbils (aerial bulbs / top sets) forms naturally mostly in the long day garlic genotypes when its scape is allowed to mature under adaptive situations.

Varied with the genotype for potentiality, garlic exhibits de-scapping stimulates bulb yield enhancement. Scape and bulbils compete with the underground bulb for resources, leading to the compromised bulb yield (Kim et al. 2019). However, manual removal of garlic scapes before the bulbils form adds to the production cost for sure. Although, the size of the seed clove is important and a bigger seed clove produces higher bulb yield (Warade and Shinde 1998); the clove weight ranging 1.5–2.0 g reported optimum for commercial garlic production (Lencha and Buke 2017). Contrariwise, de-scapping stimulates bigger individual cloves, which eventually increase the seed rate; when used for growing the next garlic crop.

Besides, low propagation rate, continuous accumulation of ruinous viruses in the field (Metwally et al. 2012) viz., *Allexivirus*, *Carlavirus*, *Potexvirus*, *Potyvirus*, *Tospovirus*, *Garlic latent virus*, etc. (Lunello et al. 2007; Majumder and Baranwal, 2009), is still the key constraint for quality planting material production of garlic, be it cloves or either bulbils. The positive part is, bulbils bearing capacity differs among genotypes and also depend on the other factors including environment. A unique garlic clone 'H5000' was recorded with a massive bulbils production rate as high as 250–300 bulbils per plant (Kajimura et al. 2000). Being small in size; bulbils demand less storage space upon harvest; this portray provides a prospect to perceive the virtue of bulbils (Fig. 5) through focused experimentation and agronomic manipulation to utilize them as an alternate planting material for garlic (Hedau and Chaudhari 2019).

## Conclusion

Garlic indeed a crop that has been continued to be an indispensable part of culinary and therapeutic purposes for humans. The journey of garlic remained fascinating and at the same time too complicated to find its true wild ancestor or close wild relatives. From the world scenario of traceable data, the importance of this crop has been reflected through the increasing area and consequently, the production. Research investigations related to garlic's germplasm, classification, propagation, bulbils, flowering potential, true seed, interspecific-hybridization, improvement and micropropagation, are still topics of thoughtful interest.

Genetic resources in the form of accessions being harboured at present in different active germplasm sites/ gene banks for conserving the garlic diversity can be studied, explored and further augmented. The use of electron beam technique for garlic mutagenesis can be explored and it may help for basic mutagenesis studies and for recovery of desirable mutants. After the discovery of seed forming potency in garlic, researchers have started to look at garlic from a different perspective and possibilities. To expand the genetic variability of economic traits, garlic flowering and fertility restoration are still to be sufficiently explored. One can also invest in thoughts about the technique of garlic bulb production using its true seeds. Standardization of efficient micropropagation protocol in garlic is a much-needed area to emphasize research efforts. It will not only make possible in vitro multiplication of garlic but with the somaclonal variation, the chance selection opportunities become open up; moreover, on the other hand, the bulbs bound to be used as a planting material can be channelled as marketable

**a** Garlic bulbils **b** Bulbils (size based grading) and cloves

**c** VL *Lahsun* 2 bulbs produced from cloves (next to scale) with bulb produced with bulbils grown crop (*with agronomical manipulations*)

**Fig. 5** Gralic bulbils of variety VL *Lahsum* 2 and subsequent bulb produced from its bulbils grown crop, compared to bulbs produced by cloves at ICAR-VPKAS, Almora, India

produce. The role of agronomical interventions post in vitro plantlets production should not be underestimated to achieve the fullest possible bulb yield.

The use of bulbils as a planting material with agronomic interventions needs to pre-consider the tackle of numerous viruses load. Then, for sure, use of bulbils as a planting material will increase the garlic availability without additional land under cultivation by redirecting the typical seed (planting material) for consumption. A retrospect of garlic's past, aptly concise status quo and dissected dimensions (Fig. 6.) from the research standpoint will certainly provide a food-for-thought to the garlic researchers.

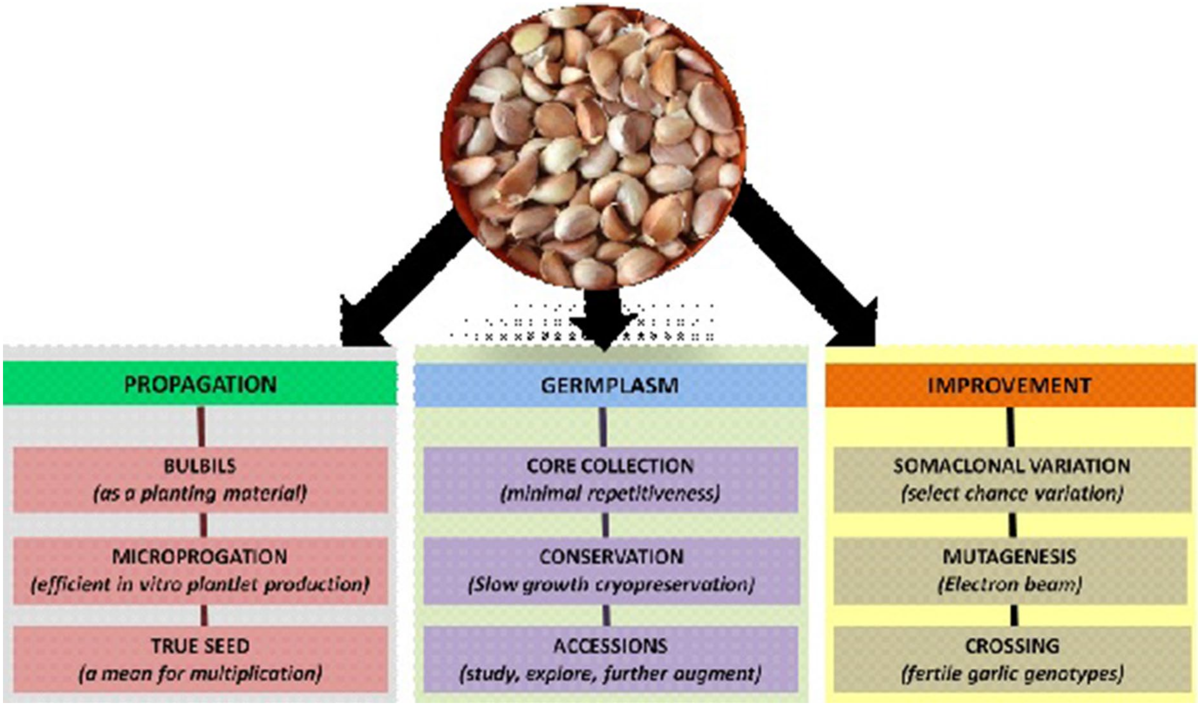



**Fig. 6** Schematic representation of the garlic dimensions which needs research attention

**Author's contribution** GVC and NKH conceived the idea, performed a literature survey, structured the draft layout and prepared the manuscript. HR provided inputs for the section on garlic's nutrient composition, phenotypic classification and provided some references for the manuscript. YPK provided some references for the manuscript, cross-checked the references and revised the style of quoting references in the manuscript. AK and LK improved the manuscript by editing different sections for the final shaping of the manuscript. All the authors have read and approved the final version of the manuscript.

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**Declarations**

**Conflict of interest** The authors declare that there is no conflict of interest.

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