Evaluation of cultivation methods and sustainable agricultural practices for improving shallot bulb production – a review

Omid Askari-Khorasgani[1], Mohammad Pessarakli*[2]

[1] *Young Researchers and Elite Club, Department of Horticulture, College of Agriculture and Natural Resources, Isfahan (Khorasgan) Branch, Islamic Azad University, Isfahan, Iran ORCID: https://orcid.org/0000-0002-8956-5977*

[2] *Professor, School of Plant Sciences, College of Agriculture and Life Sciences, The University of Arizona, Tucson, AZ 85721, USA ORCID: https://orcid.org/0000-0002-7662-2258* * Corresponding Author E-mail: Mohammad Pessarakli pessarak@email.arizona.edu

ABSTRACT

Shallot is an economically important nutritive bulb vegetable and medicinal plant from Alliaceae family. Distributed in limited regions worldwide, in most cases, shallots widely grow in very cold to moderate cold temperate climates at high elevations required to induce bolting and overcome their bulbs and true seeds dormant period. Shallot responses to agricultural management and environmental conditions vary among different species and genotypes and thus selection of the elite genotypes is a prerequisite for obtaining desired yield and quality of bulbs and true seeds. Plant material (seed or bulb), plant selection, as well as cultivation and agricultural practices (importantly fertilization, spacing, planting date, and irrigation in greenhouse or farmland) critically affect productivity, phytonutrient value and economic profit of the shallot produces. The knowledge of using biofertilizers and mulching techniques on shallots are currently evolving, but the information on the efficiency of nanobiofertilizers and eco-friendly and biodegradable mulching materials on shallots farming are still lacking. With the emphasis on sustainable agricultural systems, the efficiency of combined organic and inorganic fertilization is discussed and the potential biofertilizer agents are recommended. This review *highlights the importance of using the integrated fertilization (organic and inorganic methods combined with biofertilizers) and irrigation methods (such as two-line spray hose irrigation combined with mulching), and the practices with the highest potential to further improve shallot farming are suggested. The information on shallots breeding is still lacking and requires extensive researches in the future.*

Keywords: *Allium,* Mooseer, medicinal, herb, organic, biofertilizer, plant growth promoting fungi and bacteria, microbiome

CONTACT: Mohammad Pessarakli, Professor pessarak@email.arizona.edu School of Plant Sciences, College of Agriculture & Life Sciences, The University of Arizona, Tucson, Arizona 85721, USA.

Introduction

Shallot is an economically important nutritive vegetable and medicinal plant belongs to *Allium* as the sole genus with over 900 species in the Allieae tribe, one of four tribes of subfamily Allioiideae subfamily of monocotyledonous flowering plants in the family Amaryllidaceae, order Asparagales. Allioiideae was formerly known as Alliaceae in a separate family (Li et al. 2010; World Checklist of Selected Plant Families [WCSP] 2014; Deniz, Genç, and Sarı 2015; Major et al. 2018; Khorasani et al. 2018). Shallots are originated from Western Asia and worldwide with a weak geographically distribution are cultivated and in most cases widely grow in limited regions of few countries, largely in Asian countries. This is because they require specific edaphoclimatic conditions and agricultural management to grow, overcome bulb dormancy, induce seed talk development and reproduce bulbs and true seeds (Tendaj and Mysiak 2013; Biru 2015; Jafari et al. 2017; Rahayu, Mujiyo, and Arini 2018; Farhadi and Alizadeh Salteh 2018). Besides environmental factors, its high economic value, tasty flavour, and medicinal properties as the major alluring factors have contributed to its overexploitation, placing it among endangered species (Williams, Clubbe, and Hamilton, 2012; Ebrahimi et al. 2014). Therefore, breeding and agronomic approaches are required to design shallot populations with desired genotypes and phenotypes and to propagate the elite genotypes (vegetatively through bulb propagation or sexually through true seed reproduction) to meet their global demand and protect them from the risk of extinction.

Shallots morphological characteristics, phytochemical diversities, and productivity are greatly dependent on genetic characteristics (plant selection), environmental conditions, agronomic management and, thus, having the knowledge of these items are essential for shallot breeders and farmers to increase their yield and quality (Mansouri et al. 2015; Major et al. 2018; Buda, Agung, and Ardhana 2018; Ammar et al. 2018). Hence, considering these influential factors, the present review article represents the up-to-date information of farming methods of different shallots populations and suggests multi-disciplinary approaches for improving yield and quality of shallots, specifically through vegetative (asexual) propagation methods of shallot bulbs.

Genetic, morphological, and phytochemical diversity of shallots

Shallots are onion-like plants, but smaller in size and have separate bulbs attached at the base (Biru 2015). Of about 900 so far identified species in *Allium* genus, classified into 15 subgenera and 57 sections (hereafter sect.), approximately 140 species grow in Iran, known as Persian shallots (Fritsch and Maroofi 2010; Fritsch and Abbasi 2013; Razyfard et al. 2011; Memariani, Joharchi, and Arjmandi 2012). Persian shallot species are classified into seven subgenera and 32 sects (Friesen et al. 2006; Fritsch et al. 2009). Although many Persian shallot species are endemic to Iran, some of them are also native to the neighbouring countries such as Turkey, Pakistan, Afghanistan and Central Asia (such as Turkmenistan, Uzbekistan, Tajikistan, and Kazakhstan). Persian shallot species in Iran, such as *A. hirtifolium* Boiss. (syn. *A. stipitatum* Regel), and *A. altissimum* Regel and *A. hollandicum* R.M. Fritsch (syn. *A. aflatunense* so-called "Purple Sensation" widely cultivated as an ornamental) known as "Mooseer" (also "Musir" or "Moosir") are different from the common shallot *A. ascalonicum* in many characteristics. For instance, common shallot bulbs are pear-shaped, with the skin reddish brown in color and its cluster may contain as many as 15 bulbs, while *A. hirtifolium* bulbs are oval shaped and white skinned, typically consisting of one or sometimes two bulbs (Fritsch and Gurushidze 2009; Rezvan et al. 2011; Ismail et al. 2013; Fritsch and Abbasi 2013; Rezaei, Kafi, and Bannayan 2013; Krejčová et al. 2014). Persian shallot (mainly *A. hirtifolium* and *A. altissimum*) bulbs are traditionally used as a condiment and are also added to a variety of foods, such as salads (for example, crushed and mixed with yogurt known as "Maast-o- Mooseer" as a popular tasty salad), sauces, and pickles (Krejčová et al. 2014; Arefkhani 2017; Farhadi and Alizadeh Salteh 2018). Phenolic compounds (importantly flavonol glucosides such as quercetin-4′-glucoside and quercetin-3,4′-diglucoside), allicin, flavonoids (particularly quercetin, identified in *A. hirtifolium* ethyl acetate extract), saponins (such as a steroidal saponin so-called Cepa2 identified in *A. cepa* L. Aggregatum roots with anticancer activity), sulfur compounds (such as sulfide, disulfide [such as dialyl disulfide], trisulfide, tetrasulfide), pyrithione, and sulfur-containing pyridine *N*-oxides compounds are the main pharmacologically active compounds that can be identified in shallot populations with different distribution patterns (Krejčová et al. 2014; Aleebrahim-Dehkordy et al. 2016; Major et al. 2018). Essential oil analysis of Persian shallot *A. stipitatum* widely grown in Chahar Mahal-e Bakhtiari Province of Iran was rich in sulfur compounds and butene,1-(methylthio)-(Z) (18.21%), methyl methylthiomethyl disulfide (8.41%), dimethyl tetrasulfide (6.41%), and piperitenone oxide (4.55%) were its major phytochemical constituents. Mono-sulfur (22.42%), tri-sulfur (13.57%), tetra-sulfur (6.47%) and disulfide (1.81%) were respectively its major sulfur-containing components (Fasihzadeh, Lorigooini and Jivad 2016). Sulfur-containing compounds in Persian shallot *Allium stipitatum* Regel were mainly composed of allicin (diallyl-dithiosulfinate), diallyl disulfide (DDS), S-allylcysteine (SAC) and diallyl trisulfide (DTS) (Fasihzadeh, Lorigooini and Jivad 2016). In shallot species *A. ascalonicum* Hort., apart from sulfur compounds, furostanol saponins and flavonoids (mainly quercetin, isorhamnetin, and their glycosides) were its major metabolite constituents (Fattorusso et al. 2002). The phytochemical analysis of hydromethanolic extract of Persian shallot *A. hirtifolium* Boiss. detected 9-hexadecenoic acid, 11,14-eicosadienoic acid, and n-hexadecanoic acid as the major constituents responsible for its safe and strong antibacterial activity (Ismail et al. 2013). Phenolic compounds in ethanol extract of Persian shallot *A. hirtifolium* Boiss. have also shown moderate to–good antibacterial (MICs = 0.062 to 0.250 mg ml^{-1}) and antioxidant activities (Ghasemi Pirbalouti et al. 2015). The main mineral nutrients in shallots include N, P, K, Ca, and Zn (Major et al. 2018). Shallot nutritional value, medicinal properties, and yield are significantly affected by agronomic practices (such as spacing, fertilization, and using stimulants), land suitability (such as climate, slope, soil characteristics, and soil microorganisms), plant genetic and morphological (such as bulb weight) characteristics, and cultivation year (Biru 2015; Arefkhani 2017; Kafrawi 2017; Farhadi and Alizadeh Salteh 2018; Böttcher 2018; Fatchullah, Masnenah, and Rahman 2018; Major et al. 2018). Of 17 Persian shallot landraces from *A. hirtifolium* species, Harsin landrace had the highest dry matter (36.7%) and the highest amount of their nutrient elements were as follows: Na in Harsin, Fe and Cu in Kangavar, Mg in Koohrang, K and Mn in Sahneh, and Zn in Khomein landrace. Comparing their fatty acids, Ashtin and Sepidan landraces had the highest of linolenic acid (ω3) and linoleic acid (ω6) (Ebrahimi et al. 2008). To date, aside from the traditional remedies, numerous pharmacological properties of shallot (mostly and differently in *A. ascalonicum, A. hirtifolium,* and *A. cepa* L. Aggregatum group, the latter is classified into the common onion group) bulbs such as antioxidant, anti-inflammatory, anticancer, antibacterial, antifungal, anti-angiogenic, and antidiabetic activities have been corroborated (Mohammadi-Motlagh, Mostafaie, and Mansouri 2011; Mehdi et al. 2013; Krejčová et al. 2014; Teshima et al. 2013; Mohammadi-Motlagh et al. 2017; Khaleghi et al. 2017; Hosseini et al. 2017; Major et al. 2018; Amin et al. 2018; Karunanidhi et al. 2018; Ounjaijean et al. 2019). Yet, more studies on different shallot populations are required to provide information regarding their phytochemical diversities, nutrition and pharmaceutical values. Hence, understanding shallots genetic diversity and classification is an essential step in breeding programs and agricultural management. Thus, due to the importance of nutritional and medicinal properties of Persian shallots (Ebrahimi et al. 2008), their classification is briefly discussed to avoid confusion among farmers and genetists/breeders. In *Melanocrommyum* (Webb. & Berthel.) subgenus Persian shallot species *A. stipitatum* complex includes sect. *Procerallium* with two subsections (hereafter subsect.) *Elatae* R.M. Fritsch and *Costatae. A.* subsect. *Elatae* R.M. Fritsch consists of two species, i.e., *A. hirtifolium* and *A. altissimum*. *A*. subsect. *Costatae* includes six species, i.e., *A. pseudohollandicum* R.M. Fritsch, *A. remediorum* R.M. Fritsch, *A. bakhtiaricum* Regel, *A. jesdianum* Boiss. & Buhse, *A. kazerouni* Parsa and *A. orientoiranicum* Neshati, Zarre & R.M. Fritsch. *A.* sect. *Megaloprason* subsect. *Keratoprason* includes *A. sarawschanicum* Regel, and *A*. sect. *Pseudoprason* includes *A. hooshidaryae* Mashayekhi, Zarre & R.M. Fritsch and *A. koelzii* (Wendelbo) K. Press. & Wendelbo. Different from the members of this complex, monotypic species *A. giganteum* Regel belongs to sect. *Compactoprason* R.M. Fritsch subsect. *Erectopetala,* and *A. chelotum* Wendelbo belongs to sect. *Decipientia* (Omelczuk) R.M. Fritsch (Khorasani et al. 2018). In *Melanocrommyum* subgenus. *A. aladaghense* Memariani

& Joharchi, sp. nov. (morphologically similar to *A. kuhsorkhense* R.M. Fritsch & Joharchi), *A. elburzense* Wendelbo, *A. monophyllum* Vvedensky, *A. helicophyllum* Vvedensky, *A. pseudobodeanum* R.M. Fritsch & Matin Vvedensky *and A. cristophii* Trautvetter (an important ornamental) belong to sect. *Asteroprason* subsect. *Asteroprason* (which are endemic to Khorassan-Kopetdagh and central to eastern Alborz mountain ranges); and *A. cristophii* (an important ornamental) Trautvetter and *A. ellisii* belong to sect. *Asteroprason* subsect. *Christophiana* (which are endemic to Khorassan-Kopetdagh) (Memariani, Joharchi, and Arjmandi 2012) In *Melanocrommyum* subgenus. *Akaka* S.G. Gmelin. belongs to sect. *Acanthoprason* (Jafari et al. 2017). Apart from the most studied Persian species, i.e., *A. hirtifolium* and *A. altissimum,* the information on the influence of cultivation and agronomic practices on the other populations is scarce and require extensive investigations. The information on the breeding programs of Persian species is also lacking.

Cultivation methods, irrigation, and selection of shallots

Depending on species and genetic characteristics, shallots require about two months with low temperatures around 0 to 4 °C to overcome bulbs' dormant period. Shallots bulbs are tolerant to freezing temperatures, for example, by -12 °C for Persian shallot *A. altissimum* Regel Shirvan ecotype and -16 °C for Kalat and Tandoureh ecotypes (Rezvan et al. 2011; Farhadi and Alizadeh Salteh 2018). In Iran, shallots widely grow as endemic species in very cold to moderate cold regions. Bulbs sprouting occurs when temperature rises to 3.3 to 5.9, and plants grow well at 13 to 24 °C (Sabzevari et al. 2015; Farhadi and Alizadeh Salteh 2018). At high elevations (usually, more than 1000 m above sea level), flowering naturally occurs at 9-12 °C. However, low elevations and high temperatures above 26 °C prevent flower stalk development and flowering, which can be reinitiated by human interference for example by vernalization or hormone application [for example, by soaking bulbs and spraying plants with gibberellin (GA_3)], the effects of which vary depending on shallot genotypes and hormone dosages (Sabzevari et al. 2015; Triharyanto, Sudadi, and Rawandari 2018). Since such treatments may differentially affect plant bulb yield and size as well as seed reproduction (Triharyanto, Sudadi, and Rawandari 2018), preliminary experiments are necessary to evaluate the effects of treatments (soaking, spraying, concentrations and time of application) on different genotypes. Shallots flower stalks are commonly removed at 50% bolting to put back the energy into the bulbs and increase bulb yield (Sabzevari et al. 2015). In Iran, after 6-12-week stalk development (depending on genotype and environmental condition), shallots flowers are decapitated around mid-spring to promote bulbs growth and yield for the harvesting time at the end of spring (Sabzevari et al. 2015). Flower removal can also affect shallots phytochemicals, for example by increasing allicin content (Shahgholi et al. 2014). Well-developed shallot bulbs are then collected in late spring, disinfected, pre-cooled (at 4 °C for about two months), and subsequently they are cultivated in greenhouses (in 3:1 perlite to vermicompost) or farmlands in mid-summer for the next years (Farhadi and Alizadeh Salteh 2018). To our knowledge, no study has so far been conducted to compare the productivity (yield and quality) and economic profits of widely grown, greenhouse cultivated, and farmland cultivated bulbs and true seeds of the same species and genotypes (preferably elite genotypes when available) of shallots under the same environmental condition and agricultural management. Such a long-term (at least a 3-year) study is critically required to demonstrate which method has the highest potential for increasing shallot productivity and economic profits. Hence, the available data are represented to discuss the most efficient approaches and provide information for researches in the future. In this regard, the influence of cultivation methods and agricultural management on Persian shallot species *A. altissimum* and *A. hirtifolium* is discussed (Table 1). Persian shallot *A. hirtifolium* widely grows across the Zagros Mountains of northern (Qazvin), western (Kermanshah, Kurdistan, Lorestan), mid-west (Hamedan), and central (Charmehalbakhteyari) parts of Iran (Ghahremani-Majd and Dashi 2013). Persian shallot *A. altissimum* widely grows in mountainous regions particularly in North Khorasan Province of Iran (Rezaie et al. 2012; Sabzevari et al. 2015). To compare their productivity and responses to agricultural practices and environment, both species were cultivated in Khorasan Province in Iran. Persian shallot *A. altissimum* collected from Lorestan Province sprouted 10 days earlier than *A. hirtifolium* from Kalat, Khorasan. *A. altissimum* sprouted more quickly by receiving 586.6 growing degree days (GDD= $\Sigma\{(T_{max}+T_{min})/2\}-T_b$, where T_{max}, $T_{min,}$ and T_b are respectively maximum and minimum daily temperatures and T_b is the base temperature below of which growth stops) within 128 days, whereas *A. hirtifolium* required 621.05 GDD within 138 days to initiate bulbs sprouting in late winter. In the same way, daughter bulbs development in *A. altissimum* Lorestan landrace started 14 days earlier (concomitant with flower stalk development) than *A. hirtifolium* Kalat landrace (10 days after initiating flower stalk development) in early spring. In total, *A. altissimum* Lorestan landrace bulb sprouting to harvesting required 109 days and 1077 GDD and bulb planting to bulb harvesting period required 239 days and 1664 GDD, whereas they were 114 days and 1379 GDD and 252 days and 2000 GDD for *A. hirtifolium* Kalat landrace, respectively. However, using the best cultivation methods (50 × 10 cm^{-2} spacing, 20 bulbs m^{-2}, 20-30 g mother bulb weight), *A. hirtifolium* Kalat landrace productivity (1695.39 g m^{-2} bulb yield, 81.22 g bulb weight, 21.62 bulbs m^{-2}) in its own location (Khorasan) was outstandingly greater than *A. altissimum* Lorestan landrace (390.62 g m^{-2} bulb yield, 41.67 g bulb weight, 10.55 bulbs m^{-2}), from 30.10.2012 to 12.06.2013 (Sabzevari et al. 2015). This could be due to the adaptation of *A. hirtifolium* Kalat landrace to its location (Sabzevari et al. 2015) or different management requirements. Though increasing 20 to 30 bulbs m^{-2} markedly reduced the total yield (1695.4 to 1392.8 g m^{-2}), 30 bulbs m^{-2} significantly increased the number of bulbs

(21.6 to 44.5 bulbs m^{-2}) in Sabzevari et al.'s (2015) study for both *A. hirtifolium* Kalat landrace, but without significant influences on *A. altissimum* Lorestan landrace. Similarly, Kheirkhah, Mohammadkhani, and Ghorbanzadeh Naghab's (2017) study showed that increasing the planting density from 20 to 30 and 40 bulb m^{-2} markedly reduced bulb yield and thousand kernel weight (TKW). Comparing planting density (20, 30, and 40 bulbs m^{-2}) and P levels (0, 150, 250, 350 kg ha^{-1} triple superphosphate), the highest bulb and seed yield and TKW were obtained by using 20 bulb m^{-2} and 350 kg ha^{-1} triple superphosphate. Generally, large mother bulbs (45-55 g) (Table 1) are preferable for planting, while medium size bulbs (20-30 g) have more market value. Hence, despite reducing the total yield by planting 30 bulbs m^{-2}, the increased number of medium size bulbs and their economic value or their productivity in a longer period should also be compared to 20 bulbs m^{-2} planting density. Accordingly, the species and genotype particularly with high potential for producing daughter bulbs, location, adaptation, variations in price, bulb weight, number of bulbs and total yield should all be considered to make a sound conclusion. Moreover, the effects of all of the influential factors on yield and bulb size should be considered for the best recommendation. Bulb size can be affected by years of cultivation, cultivation methods (such as plant spacing and density, planting date, and planting material), and agricultural management (such as fertilization and hormone application like GA_3 to stimulate sprouting) (Arefkhani 2017; Triharyanto, Sudadi, and Rawandari 2018). In a seed-to-seed reproduction method, greenhouse-grown 4-week-old shallot seedlings at the 2-3 leaf stage with a height of ca. 12 cm are planted in field in early summer (for example, 28 July 2009 in Lublin, Poland) to reduce mother bulb damages (on average 26%) during overwintering (storage for planting in spring). However, a 2-4-week delay in seedling planting significantly reduces seed stalk development and seed reproduction/yield in the next year (Tendaj and Mysiak 2013). For bulb cultivation, unprecooled shallot bulbs should be pre-planted during the cold season (mostly in fall, depending on the region and shallot genotype) or stored at 4 °C for about two months to overcome dormant period and stimulate bulb sprouting (Sabzevari et al. 2015; Farhadi and Alizadeh Salteh 2018). Prior to planting, shallot bulbs are disinfected by soaking in fungicides such as Captan, Azoxystrobin, Difenoconazole or Mancozeb (approximately 2 g L^{-1} for 15 min) (Farhadi and Alizadeh Salteh 2018; Ammar et al. 2018; Sumbayak and Susila 2018). Shallot bulbs are commonly cut by a knife, contacted with ash to facilitate sprouting and shoot production, and planted 8 to 10 cm deep (Biru 2015; Farhadi and Alizadeh Salteh 2018). Shallot bulbs are harvested when leaves have turned yellow, more than 60% of the leaves have dropped, and stem's neck has turned soft (Sumbayak and Susila 2018). Depending on planting materials, bulb size, plant genotype, agricultural practices and environmental conditions, shallot bulbs approximately require about 60-day development till harvesting time in greenhouse polybags, whereas in farmlands it takes 2 to 3 years (usually 2 years for bulb and 3 years for true seed as planting materials) to reach marketable yield (Shimeles 2014; Arefkhani et al. 2017, Farhadi and Alizadeh Salteh 2018; Buda, Agung, and Ardhana 2018, Ammar et al. 2018). For example, planting true seed shallots (TSS) of *A. ascolonicum* L. Tuk tuk variety germinated within 21 days and produced the highest bulb fresh weight (30.8 t ha^{-1}) respectively 25.73%, 18.30% and 19.77% more than bulb propagated Bima Brebes, Biru Lancor and Lokal varieties in Buahan village, district of Kintamani, Bangli regency, Indonesia from 17 July till 15 October 2015 (Buda, Agung, and Ardhana 2018). Approximately, 1.5-5 kg ha^{-1} seeds (Shimeles 2014; Triharyanto, Sudadi, and Rawandari 2018), or 1.2-2 t ha^{-1} bulbs at 15 × 20 cm plant spacing and 20 bulbs m^{-2} are required as the planting materials for shallot bulb production (Tabor 2004; Cho et al. 2011; Shimeles 2014; Sabzevari et al. 2015; Arefkhani et al. 2017; Lasmini et al. 2018). Though the growth period in greenhouse is shorter than farmland for respectively bulb and seed materials, in addition to years of production, bulb and seed yield and quality (importantly bulb size and nutrition), as well as costs of production (differences between the prices of seeds and bulbs as planting materials and their marketable products, labor requirements, as well as costs of agricultural practices such as irrigation and fertilization, and buying or renting farmland and greenhouse corresponding to cultivation area and productivity) after at least a 3-year study should be taken into account for the correct assessment.

Finding the most efficient agronomic practices that has the potential to increase the number of daughter bulbs, promote seed reproduction, bulb size, bulb fresh and dry weight, yield, and phytochemicals (such as allicin, phenolic compounds and antioxidant enzyme activity), reduce inputs and increase economic profits are the chief factors for successful shallot production (Arefkhani et al. 2017; Farhadi and Alizadeh Salteh 2018). Agricultural management that improves water and nutrient uptake, sink-source balance, and photosynthesis can promote shallot productivity (Arefkhani et al. 2017; Farhadi and Alizadeh Salteh 2018). Improving shallots antioxidant enzyme activity can promote shallot physiological responses under normal and more importantly stress conditions (Farhadi and Alizadeh Salteh 2018). Agronomic practices such as fertilization by cow manure and application of stimulants (such as forchlorfenuron) have been effective in improving in different phenotypic characteristics (Arefkhani et al. 2017; Farhadi and Alizadeh Salteh 2018). However, the knowledge of using integrated fertilization and irrigation as well as fertigation and biofertilizers are scarce in Persian shallots. This is because Persian shallots widely grow or are largely cultivated by conventional farming methods. Studies indicate that phytochemical composition and contents and plant responses to agricultural practices greatly vary among shallot populations with genetic diversities (more specifically, among shallot species, ecotypes, landraces (= domesticated ecotypes by farmers), and accessions [i.e., varieties and cultivars]). In this context, in addition to agronomic practices, breeding strategies (importantly hybridization of high quality populations or advanced biotechnological approaches such as CRISPR-Cas9, which have not been so far studied in shallots) can be deployed to improve shallot yield and quality (importantly nutrition, and pharmacological values) in the future.

Using a conventional cultivation method, for example, in Surjan system (by using silver black polyethylene) in Indonesia, require 400 man-day ha^{-1} and 500 m^3 ha^{-1} water for one season of shallot planting (Sumbayak and Susila 2018). Commonly, shallots are irrigated with a 7-day interval, but not during the rainy period in winter, till plant's leaves turn yellow (Arefkhani 2017). According to Sumbayak and Susila's (2018) study, the integrated two-line spray hose irrigation (50 mm tube width [flattened] on the surface of mulch set to 130-420 mm min^{-1} m^{-1} water feed rate to cover 200 cm width of irrigated bed) with polyethylene (Sumisansui-MARK II; which is black) mulching (at 15×20 cm plant spacing in 1 m width×22 m length×0.5 m height bed dimensions and 50 cm distance between beds) was more efficient than the conventional method Surjan system. In their study, fertilization was performed by using 500 kg ha^{-1} NPK (16N, 16-P_2O_5,16 K_2O) plus 20 t ha^{-1} cow manure mixed with the 20-cm top-soil prior to mulching and then shallot "Bima Curut" seeds were planted. The two-line spray hose irrigation combined with black film polyethylene mulching improved fertilizer and water use efficiency by reducing their evaporation and leaching, reduced the costs of irrigation, fertilization and weeding, reduced labor requirement, and improved shallot growth and yield. Another field trial showed that transparent polyethylene film mulching can be more efficient than the black film by 21% increasing shallot (*A. cepa* var. *ascalonicum* Backer) marketable yield (Cho et al. 2011). The differences could be due to the effect of the film color on soil temperature. Since shallots prefer cold temperatures (at or above 0 °C to 24 °C, depending on shallot species and genotype) during the growth period, probably the black film negatively affected shallot growth by increasing temperature more than the white one. Hence, the integrated two-line spray hose irrigation with white mulching may be more efficient than the integrated method with black mulching, which remains to be verified. Using the eco-friendly or biodegradable mulching materials could further increase the advantages of this integrated method, for example by providing nutrient, reducing the costs of buying plastic film and fertilizers, improving soil characteristics and also ecosystem health.

Conventional fertilization practices

Appropriate fertilization improves sink-source balance, leave growth and, thereby, photosynthesis, and bulb and seed yield (Arefkhani 2017). Since excessive use of N increases vegetative growth of shallot and reduces bulb weight (Arefkhani et al. 2017), contaminates ecosystem and damages human health (by increasing the risk of diseases such as various cancers, adverse reproductive outcomes-especially neural tube defects-, diabetes, and thyroid conditions), ideal fertilization methods such as adequate use of N and P combined with organic fertilizers such as sewage, manure and mulching would uphold advantages of shallot farming (Ward 2009; Zhang, Li, and Li 2019; Gu et al. 2019). Depending on shallot genetic diversity, application of 208 to 285 kg ha^{-1} N fertilizer during cultivation of true seed shallot varieties (Tuktuk 285, Bima Brebes 283, Biru Lancor 208, and Lokal 241 kg ha^{-1} N) markedly increased bulb diameter and fresh weight in Bali, Indonesia (with loamy sand texture, pH 6.8, 3.2% C, 0.18 N, 81.19 ppm available P, 631.4 ppm exchangeable K, and very low electrical conductivity (EC)) (Buda, Agung, and Ardhana 2018). Several field studies have reported the beneficial effects of N:P:K in the ranges of 100-280 kg ha^{-1} N, 120-160 kg ha^{-1} P, and 50-200 kg ha^{-1} K on improving shallot yield, depending on shallot accessions, cultivation practices (importantly spacing and irrigation) and environmental conditions (importantly soil characteristic) (Mansouri et al. 2015; Ammar et al. 2018). In A. *altissimum* Regel, cultivated bulbs in greenhouse pots filled with 6% sand, 24% silt, and 16% loam, the highest bulb dry yield was obtained by applying 210 kg ha^{-1} N (comparing 0, 70, 140, and 210 kg ha^{-1} doses) and 50 kg ha^{-1} P_2O_5 (comparing 0, 50, and 100 kg ha^{-1} doses), while the influence of K was insignificant, likely due to its sufficient content in soil (10.2 mg kg^{-1}) (Arefi et al. 2016). Hence, soil analysis is required prior to any recommendation. According to Ammar et al.'s (2018) greenhouse study, cultivated shallot bulbs 3 cm deep in polybags filled with 2:1 (v:v) ratio of fertile alluvial soil:cow manure, application of 100 kg ha^{-1} N, 160 kg ha^{-1} P, and 50 kg ha^{-1} K were effective in improving the number of bulbs per clump, bulb dry weight, and total bulb dry weight per clump. The higher amount of N increased the bulb fresh weight most likely by increasing water absorption and could be hazardous for humans and ecosystem health. Besides, using unnecessary inputs increases the cost of shallot farming and can negatively affect plant physiology and nutrition. For example, excessive N can negatively affect phenolic compounds (Major et al. 2018). According to Mansouri and coworkers' (2015) field study, 260 kg ha^{-1} N, 2227 m^3 water ha^{-1}, and 16.7 plant m^2 led to optimal result in economic scenario, while the desired results for environmental and integrated economic-environmental scenarios were respectively obtained by using 100 kg ha^{-1} N, 1500 m^3 water ha^{-1}, and 16.54 plant m^2, as well as 169 kg ha^{-1} N, 2025 m^3 water ha^{-1}, and 17.7 plant m^2. Like organic manure, but with a stronger positive impact, Biourine can be used to reduce the amount of N input and increase shallots productivity. Application of 1000 L ha^{-1} Biourine, 100 kg N ha^{-1} (ZA), 50 kg P_2O_5 ha^{-1} (superphosphate 36, SP36), and 70 kg K_2O ha^{-1} (potassium chloride, KCl) resulted the highest productivity (18.6 t ha^{-1} in one growing season) (Santosa et al. 2015), which can be further improved by adding organic manure, for example 10 t ha^{-1} cow manure, or with a superior method by using organic fertilizer and/or biofertilizers discussed in the following section.

Sulfur fertilizer greatly improves onion yield and quality. Depending on the cultivar and fertilization dosages, 40 and 50 kg ha^{-1} sulfur fertilizer increased total polyphenols, quercetin, total sulfur content in onion (*A. cepa* L.) cultivar (Tóth et al. 2018). Thus, due to similarities between onion and shallot and the importance of sulfur-containing components in shallot, sulfur fertilizer may have a high potential for improving yield and quality of shallot accessions, as well. Yet, the relationships between shallot productivity, genetic characteristics, sulfur dosages and their integrated effects with other fertilizers, cultivation and irrigation practices and environmental conditions remain to be investigated. In addition to agricultural management, proper post-harvest handling is also necessary for preserving the quality of shallots. For example, modified atmospheric bulk packaging containing 10% CO_2 and 90% N_2 in Ony/LLDPE at 5±1 °C and 85-90% relative humidity has been effective in preserving volatile compounds of the freshly packaged shallot Puree *A. ascalonium* bulbs for up to 12 weeks (Noor Azizah et al. 2013). Future studies are yet required to assess the influence of sulfur fertilizer, importantly in the integrated system using the best irrigation method and biofertilizers on improving shallot yield and phytonutrients, particularly sulfur-containing compounds.

Organic fertilizers, biofertilizers, and integrated fertilization practices

Application of organic fertilizers promote soil biological and physico-chemical characteristics and together with biofertilizers are important in sustainable agricultural system. Adding plant growth promoting rhizobacteria (PGPR) and plant growth-promoting fungi (PGPF) to soil and/or both organic and inorganic fertilizers can further increase plant productivity, for example, by decomposing organic fertilizers and consequently increasing the efficacy of fertilizers, increasing nutrient availability, reducing the need for inorganic inputs and thus reducing their negative impact and costs, promoting population and diversity of beneficial microorganisms and suppressing pathogenic organisms (Zhang et al. 2018;

Fernandes et al. 2018; Lasmini et al. 2018; Akyol et al. 2018). For example, *Trichoderma* spp. are well-known PGPF that enhance plant nutrient uptake, production of growth hormones, and protect plants from pathogen infection (by suppressing pathogenic fungi and improving plant health and growth). *Trichoderma* biofertilizer improves soil fungal and microbial population and diversity as well as soil nutrient availability (for example, by increasing P-solubilization). Compared to a single application, combination of *Trichoderma* biofertilizer and organic fertilizers, for example, by inoculating 9,000 kg ha^{-1} composted cattle manure with *Trichoderma* biofertilizer, induces stronger positive impact on plant productivity and inhibits the negative effects of using excessive organic and synthetic fertilizers (i.e. undue nitrate and phosphate contents, which causes soil hardening and/or salinization and destroys soil physico-chemical properties and microorganisms activity) (Zhang et al. 2018). The integrated nutrient management can be used to improve nitrogen use efficiency (NUE), plant productivity, and environmental health. For instance, the highest onion bulb yield was obtained by applying 50% of recommended N dose combined with 5 t ha^{-1} vermicompost (Gebremichael et al. 2017), which could also reduce N leaching into groundwater and runoff toward surface water, reduce N_2O emission, promote N uptake by N_2-fixation and soil health (Askari-Khorasgani et al. 2019a). After planting shallot (*A. cepa* L. var. aggregatum) bulbs at 15×20 cm spacing, integrated fertilization by applying 3 t ha^{-1} cow dung bokashi (containing cow manure, *Gliricidia* sp. leaves, microorganism sources such as *Lactobacillus*, phosphate solubilizing bacteria and yeast as well as nutrient elements) coupled with 200 kg ha^{-1} NPK efficiently increased bulb yield and promoted soil fertility by increasing organic C (from 0.66 to 3.28%), N-fixing bacteria (from 27×10^5 to 47×10^6 CFU ml^{-1}), and phosphate solubilizing bacteria (20×10^3 to 90×10^3 CFU ml^{-1}) (Lasmini et al. 2018). Besides, fertile soils with a good proportion of organic matters, particularly in decomposed form of humus, have high water holding capacity (WHC), lower water evaporation (which dry slowly in arid and semi-arid conditions) and, therefore, improved plant productivity and soil properties (such as biological activities, organic C, pH, cation exchange capacity (CEC), structure, aeration, as well as water and nutrient [importantly P and K] availability) (Lasmini et al. 2018).

Depending on the species and genotypes, shallots differently respond to fertilizers. For example, with significant differences among *A. ascalonicum* L. varieties, 1 kg m^2 urbane waste compost (with greater efficacy than biochar) was the most effective treatment for increasing the yield of Super Philip variety more than Bima Brebes and Medan varieties (Luta, Hanafiah, and Sabrina 2018). The effectiveness of urbane waste compost or vermicompost can further be improved by adding humectant agents to improve WHC, which can particularly improve seed germination and survival in hard conditions (Paradelo, Basanta, and Barral 2019), but has not been studied in shallots. An experiment showed that long-term sewage sludge-amended soil provided more available P compared to unfertilized, NPK, manure, and compost-amended soils (Glæsner et al. 2019). The efficacy of combined application of 250 kg ha^{-1} 15-15-15 NPK ratio and *Trichoderma* biofertilizer on increasing shallot bulb yield, single bulb (8.58) and bulb weight per clump (40.97) has been verified (Fatchullah, Masnenah, and Abdul Rahman 2018). Comparing organic fertilizers, poultry manure (10 t ha^{-1}) had the highest efficiency on improving onion (*A. cepa* L.) productivity more than farmyard manure from a dairy farm and spent mushroom compost, with the highest positive impact on Parachinar-Local cultivar (Ali et al. 2018). In *A. ascalonicum* L. var. Kramat 1 field experiment, when PGPR fertilizer (20 ml PGPR in one liter of water for two plants with 3-week intervals) was added to chicken manure and NPK fertilizers suppressed Fusarium wilt and improved plant productivity. *Trichoderma viride*, *Pseudomonas fluorescens,* and *Streptomyces* sp. bacteria are capable of suppressing pathogenic diseases such as *Ralstonia solanacearum* and *Fusarium oxysporum* (responsible for fusarium wilt disease) in different plant fields (Fernandes et al. 2018). Reducing the need for NPK by 50%, 20 t ha^{-1} chicken manure was more efficient than cow manure, paitan (*Tithonia diversifolia*), *Crotalaria juncea*, urea, SP36, and KCl in increasing shallot *A. ascalonicum* L. yield (Wibowo, Heddy, and Sugito 2018). With a dual function, Nitrobacter biofertilizer can control pathogenic diseases such as *Fusarium, Phytophthora, Pythium* and also promote shallot productivity. The concentration of 60 ml *Nitrobacter* biofertilizer per 3 L water was the most efficient dose for improving the bulb yield of Bangkok variety (Saharuddin et al. 2018). Yet, understanding the interactions between these biofertilizer agents, the efficiency of their integrated effects in different biofertilizer formulations and the efficacy of their co-inoculation with different PGPF and PGPR and joint application with organic and inorganic fertilizers during shallot production require extensive studies for the best recommendations.

Cold tolerant *Trichoderma* species such as *Trichoderma harzianum* AK20G strain (capable of growing at 5 °C) such as *Trichoderma gamsii*, *Trichoderma velutinum*, and *Hypocrea lixii* have been effective in improving plant yield and quality and controlling diseases such as Fusarium wilt (Shanmugam, Chugh, and Sharma 2015). *Bacillus amyloliquefaciens* is a cold tolerant bacterium NBRI-SN13 (SN13) that confer tolerance to various stresses such as salt, drought, desiccation, heat, cold, and freezing by improving hormone and protein homeostasis, ROS detoxification, ACCD production, tricalcium phosphate solubilization, proline and other osmolytes production, and altering the expression patterns of stress-responsive genes coding for dehydrins, glutathione *S*-transferase (GST), LEAs, non-apical meristem (NAM), glucosyltransferases, Rab-like GTPase activators, myotubularin (GRAM), and natural resistance-associated macrophage protein 6 (NRAMP6) (Askari-Khorasgani et al. 2019b). Comparing different auxin producing bacteria, *Bacillus* sp. rhizobacterium containing menaquinone with eleven isoprene units (MK-11) had the greatest stimulatory effect on producing indole-3-acetic acid (IAA) and, thereby, improving shallot bulb dry weight (Kafrawi et al. 2017). Symbiotic performance and its positive impact on plant production can further be improved by selecting stress tolerant endemic symbiont strains with optimal plant-environmental-multisymbiotic relationships, precise agricultural management (for example, regulated deficit irrigation and fertilization) and breeding strategies (such as microbiome breeding) (Askari-Khorasgani et al. 2019a,b; Fernandes et al. 2018). For instance, *Azospirillum* spp. and *Pseudomonas striata*, and *Rhizobium* spp. co-inoculation has been more effective than a single inoculation to promote the productivity of pigeon pea (Askari-Khorasgani et al. 2019a). Since specific *Bacillus* species compete with other microorganisms like the inhibitory effects of *Bacillus* sp. BS061 on the mycelial growth of *Botrytis cinerea* (Kim et al. 2013), evaluation of their interactions and integrative effects is essential when different bacteria and fungi are combined in formulations. For example, *Glomus intraradices* and *B. subtilis* co-inoculation synergistically and significantly (about 77% more than control) improved *Lactuca sativa* growth more than singly inoculated plants (Kohler et al. 2007). Extracts of the brown seaweed *Ascophyllum nodosum* properly functions at low temperatures and promote plant growth and quality (for example by increasing phenolic and flavonoid compounds, antioxidant activity and Fe^{2+} chelating ability) and tolerance to various stresses (such as disease, drought, salinity, cold, and freezing) (Askari-Khorasgani et al. 2019b). A single application of nano-size calcium-based fertilizer pulverizations and its joint application with *A. nodosum* extract were both effective in improving growth, nutrition, and stress tolerance (Sabir et al. 2014). Commercial oak extract, commercial biostimulant Kelpak® derived from brown seaweed *Ecklonia maxima* (Osbeck) Papenfuss (*Phaeophyceae*), biostimulant EXPANDO®, chitosan (a biodegradable organic compound), PGPR such as *Pantoea dispersa* and *Burkholderia phytofirmans*, and Antarctic basidiomycetous yeast *Mrakia blollopis* are also capable of enhancing tolerance to low temperatures and, thus, might properly function in cold regions to increase shallot productivity (see Askari-Khorasgani et al. 2019b). Cold tolerant symbionts have been reviewed by Askari-Khorasgani et al. (2019a). However, future studies are required to demonstrate their influence on shallots. *Saccharomyces cerevisiae*, *Beauveria bassiana* (Lonhienne et al. 2014; Ram et al. 2018), *Saccharomyces cerevisiae* × *Saccharomyces kudriavzevii* natural hybrid (Ortiz-Tovar et al. 2019), *Serratia marcescens* strain SRM (MTCC 8708), phosphate-solubilizing *Acinetobacter rhizosphaerae* bacterial strain BIHB 723 (Selvakumar et al. 2008a; Gulati et al. 2009), a filamentous soil fungus, *Aspergillus niger* (Kohler et al. 2007), a psychrophilic yeast, *Glaciozyma antarctica* PI12 (Wong et al. 2019), *Pantoea dispersa* 1A (MTCC 8706) (Selvakumar et al. 2008b) are also some of the other good candidates as the biofertilizer agents to be investigated during shallot production.

Concluding remarks and future prospects

Because of the similarities among *Allium* species, the suggested agricultural management may provide the same advantages during cultivation of onion, garlic, leek, rakkyo, and chives, as well, and, thus, worth examining. Considering the availability and the prices of fertilizers, selection of urbane waste compost, vermicompost, cow dung bokashi, sewage sludge, as well as chicken/poultry manure as the organic substrates, their combination with each other, humectants, biofertilizers, and inorganic fertilizers would be good candidates for future investigations. Integrated fertilization (by applying organic, inorganic and bio fertilizers) and irrigation (two-line spray hose irrigation combined with mulching) are required to be carried out during the cultivation of different shallots in different locations and environmental conditions for the best recommendations. The present work suggests that agricultural practices by combining soil amendments and fertilizers (such as biofertilizers, Biourine, organic manure) to economic-environmental scenario (169 kg ha^{-}

^{1} N [by using 50 kg ha^{-1} N + 1000 L ha^{-1} Biourine + 20 t ha^{-1} chicken manure or 20 to 40 t ha^{-1} cow manure or other organic fertilizers + biofertilizers or nanobiofertilizers], 2025 m^{3} water ha^{-1} [by two-line spray hose irrigation combined with white mulching], and 17.7 plant m^{2} [by using 45-55 g bulbs weight, 20 bulbs m^{-2}, 15 × 20 cm^{-2} spacing]). 1-(2-Chloro-4-pyridyl)-3-phenylurea (known as forchlorfenuron; CPPU) can be added to this formulation to evaluate its effectiveness for future recommendations.

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Table 1. Effects of cultivation practices and agricultural management on productivity of Persian shallots *A. altissimum* and *A. hirtifolium*.

Shallot Cultivar	Year & location	Spacing	Planting date to harvesting time	Fertilization	Seed yield	Bulb FW (g)	Bulb DW (g)	Biochemistry	Ref.
A. altissimum	2013-14 Shirvan, Mashhad, Iran, in farmland	50 × 10 cm^{-2}, 30 bulb m^{-2}, 45-55 g mother bulb weight	Aug 21, 2013 (mid-summer) to Jun 15, 2014 (late spring)	60 t ha^{-1} cow manure +	6342 seeds per plant; 7.8 g per 1000 seeds; 207 capsule per plant	Highest FW			(Arefkhani 2017)
				40 t ha^{-1} cow manure	5974 seeds per plant; 7.0 g per 1000 seeds; 172 capsule per plant		Highest DW		
A. hirtifolium	2014-15 Tabriz, Iran, in greenhouse pots (3 perlite : 1 vermicompost)	Medium size bulbs were planted in greenhouse pots. CPPU was sprayed on 2-, 4-, and 6-week grown plants	During 60-day development in spring from Apr 21, 2014 to Jun 21, 2014	100 mg L^{-1} foliar spraying CPPU		91.6	Highest DW 19.3	Highest antioxidant enzyme activity (74.5%)	(Farhadi and Alizadeh Salteh 2018)
				5 mg L^{-1} pre-treatment (soaking for 24 h) and 100 mg L^{-1} foliar spraying CPPU		Highest FW 91.7	Highest DW 19.3 (CPPU markedly improved DW)	Highest phenol content (1.585 mg GAE g^{-1} FW)	
				10 mg L^{-1} pre-treatment (soaking for 24 h) and 100			Highest (19.7) DW and protein content	High phenol (1.2 mg GAE g^{-1} FW) content (CPPU	

		mg L^{-1} foliar spraying CPPU		(10.9 mg g^{-1} FW)	markedly improved phenols and antioxidant activity)

GAE, gallic acid equivalent; FW, fresh weight; DW, dry weight; CPPU, 1-(2-Chloro-4-pyridyl)-3-phenylurea known as forchlorfenuron