



## Review article

Drought adaptive microbes as bioinoculants for the horticultural crops<sup>☆</sup>Divjot Kour<sup>a</sup>, Sofia Shareif Khan<sup>b</sup>, Tanvir Kaur<sup>c</sup>, Harpreet Kour<sup>d</sup>, Gagandeep Singh<sup>e</sup>, Ashok Yadav<sup>f</sup>, Ajar Nath Yadav<sup>c,\*</sup><sup>a</sup> Department of Microbiology, Akal College of Basic Sciences, Eternal University, Baru Sahib, Sirmour 173101, India<sup>b</sup> Shri Mata Vaishno Devi University, Katra, Jammu and Kashmir, 182320, India<sup>c</sup> Department of Biotechnology, Dr. Khem Singh Gill Akal College of Agriculture, Eternal University, Baru Sahib, Sirmour 173101, India<sup>d</sup> Department of Botany, University of Jammu, Jammu and Kashmir, 180006, India<sup>e</sup> Department of Animal Husbandary, National Dairy Research Institute, Karnal, 132001, India<sup>f</sup> Department of Botany, Institute of Science, Banaras Hindu University, Varanasi, Uttar Pradesh, India

## ARTICLE INFO

## Keywords:

Biofertilizers  
Biopesticides  
Drought stress  
Horticulture  
Mitigation  
Stress adaptive microbes

## ABSTRACT

Drought stress is among the most destructive stresses for agricultural productivity. It interferes with normal metabolic activities of the plants resulting, a negative impact on physiology and morphology of the plants. The management of drought stress requires various adaptive and alleviation strategies in which stress adaptive microbiomes are exquisite bioresources for plant growth and alleviation of drought stress. Diverse drought adaptive microbes belonging to genera *Achromobacter*, *Arthrobacter*, *Aspergillus*, *Bacillus*, *Pseudomonas*, *Penicillium* and *Streptomyces* have been reported worldwide. These bioresources exhibit a wide range of mechanisms such as helping plant in nutrient acquisition, producing growth regulators, lowering the levels of stress ethylene, increasing the concentration of osmolytes, and preventing oxidative damage under water deficit environmental conditions. Horticulture is one of the potential agricultural sectors to speed up the economy, poverty and generation of employment for livelihood. The applications of drought adaptive plant growth promoting (PGP) microbes as biofertilizers and biopesticides for horticulture is a potential strategy to improve the productivity and protection of horticultural crops from abiotic and biotic stresses for agricultural sustainability.

## 1. Introduction

Scarcity of water is one of the major limitations for the plant growth and productivity. The yield losses due to drought stress exceed the losses from presence of any other environmental stress due to critical factors including severity and duration of the stress. Drought stress impairs germination and reduces seedling (Harris et al., 2002; Kaya et al., 2006). Cell division, cell enlargement and differentiation under the drought is greatly affected, which directly influences the plant growth and productivity. Nutritional imbalance under water deficit conditions further depresses plant growth by affecting uptake of the nutrients, and their transport, and distribution (Rouphael et al., 2012). Drought stress reduces the rate of photosynthesis due to decrease in leaf expansion, stomatal closure, membrane damage, disturbed enzymatic activities, and premature leaf senescence (Farooq et al., 2012; Wahid et al., 2005). Decline of Rubisco activity under severe drought conditions limit photosynthesis (Bota et al., 2004). Further, drought stresses limits the

size of the source and sink tissues and impairs phloem loading, assimilate translocation and dry matter partitioning (Farooq et al., 2009). Scarcity of water has been reported to decrease photosynthetic rates and water potentials in leaves, flowers and pods as well as leaf sucrose and starch concentrations in soybean (Liu et al., 2004).

Plants exhibit a range of the physiological and biochemical mechanisms which helps them to resist drought stress by increasing diffusive resistance, water absorption with deep root systems, and reducing loss through transpiration by smaller and succulent leaves (Farooq et al., 2012). Abscisic acid (ABA) is another important response mechanism synthesized under stressful conditions. Plant increases the accumulation of the osmolytes such as glycine betaine and proline to prevent osmotic imbalance. Transgenic plants harboring drought-inducible genes have shown increased drought tolerance (Seki et al., 2007). The alleviation and management of the drought stress is a major challenge though the innovative approaches using biochemical and molecular mechanisms. Paradigm has greatly shifted towards the adoption of the alternative

<sup>☆</sup> This article is a part of the "Irrigation and Fertilizer Management" Special issue.

\* Corresponding author.

E-mail address: [ajarbiotech@gmail.com](mailto:ajarbiotech@gmail.com) (A.N. Yadav).

strategies including the use of the stress adaptive phytomicrobiomes for amelioration of the drought (Kour and Yadav, 2020; Yadav et al., 2020). Diverse groups of stress adaptive microbes have been reported from a wide range of hosts. *Azotobacter salinestris* and *Azotobacter chroococcum* have been reported as plant growth promoter and alleviator of drought stress from soil collected from pastures and crops (Shirinbayan et al., 2019). *Acinetobacter calcoaceticus*, *Penicillium* sp., *Pseudomonas libanensis* and *Streptomyces laurentii* have been reported from different cereal crops (Kour et al., 2020a, 2020b, 2020c).

Horticultural crops majorly consist of fruits, medicinal plants, vegetables, plantation crops, spices and flowers. They play a vital role in economy and prosperity of the nation. Microbes associated with plant in natural as well as in stress environmental conditions could be utilized as bioinoculants for horticultural crops. Microbial diversity associated with horticultural crops has been reported including different species of *Burkholderia*, *Enterobacter*, *Pseudomonas* and *Rahnella* from apple (Passos et al., 2014; Soni et al., 2016), *Azotobacter*, *Bacillus*, *Micrococcus* and *Pseudomonas* from pea (Nazir et al., 2020), *Aeromonas*, *Bacillus*, *Chryseobacterium*, *Delftia*, *Enterobacter*, *Klebsiella*, *Kosakonia*, *Pseudomonas*, *Sphingobacterium* and *Stenotrophomonas* from tomato (Guerrieri et al., 2020; Hariprasad et al., 2014). In horticultural production, plant-microbe interactions may be considered the main factor for plant growth promotion and protection against abiotic and biotic stresses. Applications of the drought adaptive microbes as bioinoculants are an eco-friendly, economical and sustainable approach for plant growth, protection and mitigation of water deficit stress in plants (Ansari and Ahmad, 2019). The present review deals with the effect of the drought stress on horticultural crops and their management using drought adaptive microbial inoculants as biofertilizer or biopesticides for agricultural sustainability.

## 2. Drought affected regions worldwide

Drought is defined by the World Meteorological Organization (WMO) as “a dearth of rainfall in respect to the long term mean” distressing a large area for one or several seasons or years (Hounam et al., 1975). Worldwide 42% of the total land area is jacketed by dryland, which is abode to almost 3 billion populations. Between 1980 and 2000, the drylands have augmented in area by 9.2% affecting human lives and the

environment, such as a diminution in agricultural land, mortality and loss of biodiversity (Mirzabaev et al., 2019). Water deficit conditions are present in the all continents of the world. Specifically, in the Tropics and Subtropics, drought has become more rampant and is anticipated to exacerbate its duration and severity (Sheffield et al., 2012). South Asian regions including India, Nepal, and Pakistan have been regularly impacted by severe water scarcity from the beginning of the 21<sup>st</sup> century (Miyan, 2015) (Figure 1).

### 2.1. India

In India, drought is one of the formidable natural disasters that affect food production, the economy as well as the morale of millions of farmers. India has faced frequent and relentless drought in the last few decades and stands as one of the most vulnerable drought-prone countries in the world (Mishra et al., 2019). Drought of 1987 being the horrendous with an overall rainfall deficit of 19% and during this period approximately 60% of the crop area and over 85 million people were affected. Major drought-prone regions include eastern Maharashtra, northern Karnataka, Andhra Pradesh, Odisha, Gujarat, Telangana, and Rajasthan.

### 2.2. Afghanistan

Afghanistan is among the driest and most desolate countries in the world. About 2.5 million people have been affected, whenever a drought occurs, the southern parts of the country lose about 60–80% of animals. Crops dry up, resulting in starvation and exodus of people. Furthermore, according to Přivara and Přivarová (2019) during the period of 1998–2006 Afghanistan observed the longest and utmost drought in the last five decades. According to World Food Programme (WFP) 2003. Afghanistan is prone to the nationwide drought every 2–3 decades (Muhammad et al., 2017).

### 2.3. Pakistan

Between 1998–2002, Pakistan experienced the grievous drought in 50 years (Portal, 2011). Now the situation has gotten shoddier and the government states that a shortage of water and food threatens nearly three

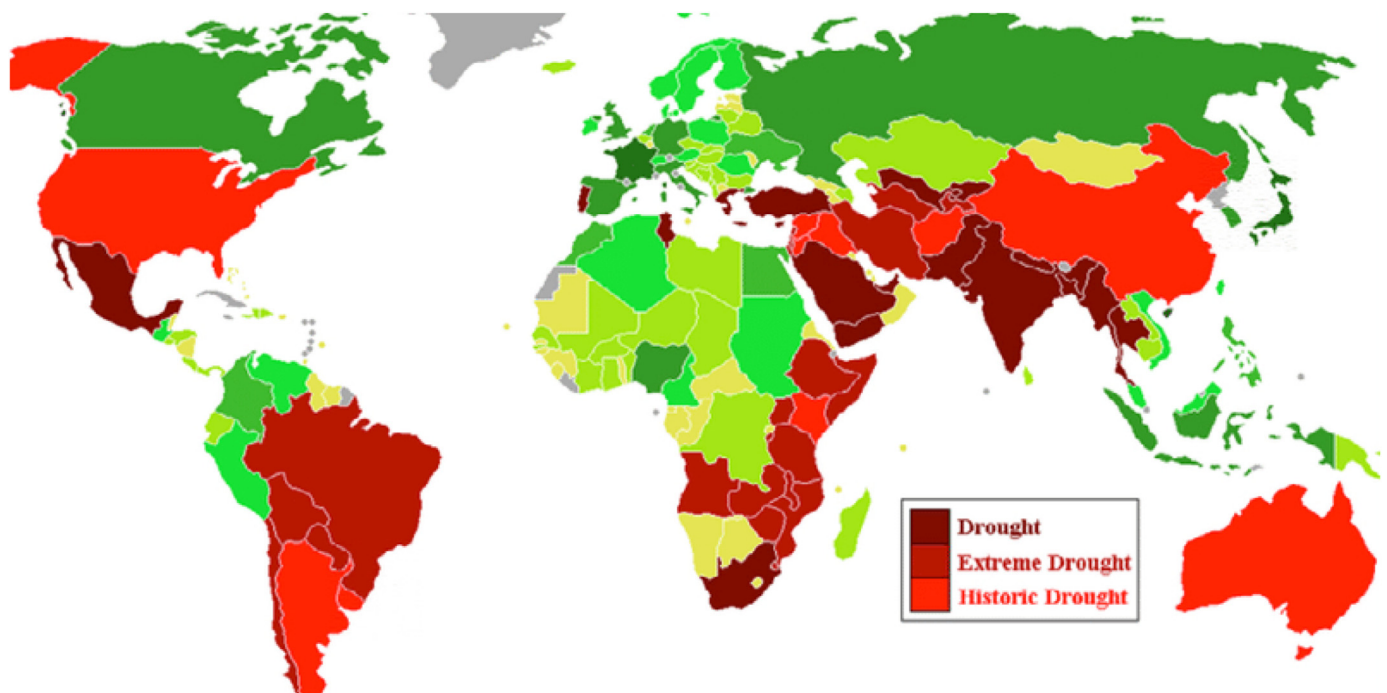


Figure 1. Global Drought Map (unitedcats.wordpress.com).

million people. The Thar Desert in the southern part of the country has been abandoned as people and livestock migrate in search of human conditions. Pakistan is expected to face absolute water scarcity by 2025 as the country's largest freshwater supplier; the Indus basin continues to dry up.

#### 2.4. Nepal

The historical droughts in Nepal were recorded in 1972, 1977, 1982, and 1992. Since 2002, the country has been experiencing frequent dry spells and during the years 2002, 2004, 2005, and 2006 the country faced dry bouts in both dry and wet monsoon. The 2008–2009 winter drought in Nepal was the worst on record (Adhikari, 2018). In particular, climate variability has caused and accelerated water stress conditions in Nepal with a negative impact on agricultural production (Hamal et al., 2020; Wang et al., 2013).

#### 2.5. Sri Lanka

Sri Lanka, located in the tropics, has experienced high-intensity cyclical droughts, occurring in intervals of three to four years. The populace of this island nation has stumbled upon a streak of inimical impacts on their economic and social life. Even the wettest parts of Sri Lanka, such as Ratnapura, have lately encountered recurrent scathing droughts. As per the statistical data of the Disaster Management Center of Sri Lanka, the country had egregious droughts in 2001, 2004, 2012, 2014, and 2016. Due to the lack of expected amount of rainfall, Sri Lanka witnessed an exigent period during 2016–2017, which caused an absence of two consecutive monsoon rainfalls.

#### 2.6. Bangladesh

Bangladesh every year experiences drought from November to May due to low rainfall. During the 1998–1999 dry seasons, in some areas of the North-west, the South-west and central zones experienced no rainfall for several months. The frequency of the droughts has increased in past few decades. Between 1949 and 1991, droughts occurred 24 times in Bangladesh while acerbic droughts thumped the country in 1951, 1957, 1958, 1961, 1972, 1975, 1981, 1982, 1984, and 1989 and past droughts have typically affected about 47% area of the country and 53% of the population (Adnan, 1993). Bangladesh also witnessed droughts in 1973, 1978, 1979, 1981, 1982, 1989, 1992, 1994, and 1995 which were of high magnitude (Adnan, 1993; Hossain, 1990). The droughts of 1973, 1979, and 1994–1995 were the worst in recent history (Murshid, 1987; Rahman, 1995).

#### 2.7. Bhutan

Bhutan has been experiencing drastic mutations in its climate and weather patterns. Although evidential data and information is restrained, yet a few case studies have been made by individual municipalities or agencies and have reflected their observations on selected sites. The winter of 2005 and 2006 faced unusually dry winter with no rain and snow (Bhutan, 2006).

#### 2.8. Cambodia and Lao PDR

Cambodia eyeballs frequent droughts, and widespread droughts occurred throughout the country in 1986–87, 1994, 1997–98, 2002, and 2005. Droughts are speculated one of the most frequent and detrimental disasters in Lao PDR. It experienced moderate to severe droughts in the years 1961, 1966, 1971, 1978, 1984, 1994, 1995, 1996 and 2009 that caused damage to lives and properties (Miyani, 2015).

#### 2.9. Yemen

Drought remains the most recurrent and grave ecological threat in the Middle East area. In Yemen, drought has been affecting both livelihood

and sustainable advancement of the country. Yemen was gravely affected by severe droughts from 2007 to 2009 and it has become an ominous devastation in the country (DhaifAllah et al., 2018).

#### 2.10. Australia

Australia has one of the most variable climates in the world and has eyeballed a significant dwindle in precipitation levels since 1994 (Hennessy et al., 2008). Deficiencies in northern Australia inflated in 2013–14, leading to a protracted drought period in certain parts of Queensland. Between 2017 and 2019, Australia across much of eastern and Queensland, New South Wales and Victoria experienced arduous drought which also extended into parts of South and Western Australia. A severe drought in Australia in 2006 abridged the national crop of winter cereal by 36 % leaving majority of farmers in financial crisis (Wong et al., 2010).

#### 2.11. China

In recent times, many regions of China including northern and southwest parts have been stumbling upon importunate drought that leaves millions of people on the brink of starvation. Crops wilt while farmers and ranchers desperately need water for their farmland and animals. In Shanxi Province, about three million population face poignant shortage of water while a third of the wheat crop in the area dries up due to dearth of irrigation. The deserts of China are fanning out at an annual average of 1,300 square miles a situation that has seen the government deploy soldiers to plant trees. Over the past century, water scarcity in China has caused 70–80 billion Kg per year food loss in China over the past century, corresponding to 17 % of the total yield (Liu et al., 2013).

#### 2.12. Africa

The most perpetuated and widespread droughts ensued in 1973 and 1984, when almost all the African countries were affected, and in 1992 all southern African countries witnessed extreme food shortages. Many gruesome and prolonged droughts were recorded in the recent past such as the 1999–2002 drought in Northwest Africa (1970s) and 1980s droughts in West Africa (Sahel), 2010–2011 drought in East Africa (Horn of Africa) and 2001–2003 drought in Southern and Southeast Africa to name a few. The drought of 2010–2011 raised the price of maize in Kenya by 246 % over the period of a year (Funk, 2011). The Sahara Desert enveloped a large part of Morocco. About 18.22% of the country's arable land is under vegetation, 12.62% is forest cover while the rest is desert. The country is drought prone and Africa's 5<sup>th</sup> largest economy. The government has set up a \$633 million contingency plan to mitigate the effects of the recurrent droughts.

### 3. Effect of drought stress on horticultural crops

Horticulture is an important section of agriculture which has established its importance in different aspects of innovation, promoting crop diversification, improving land use, generating employment opportunities and providing nutritional security to the people (Bisognin, 2011). In fact, horticulture sector of India makes about 30% contribution in agricultural gross domestic product (GDP) and annual production has been estimated to be 91 million tonnes (Datta, 2013). The demand of the horticulture industry is increasing even more with the growing population (Sonah et al., 2011). On the contrary, the changing climate impact agricultural sector in several ways such as frequent droughts, floods, spread of new diseases, reduction in productivity and faster phenological development (Snyder, 2017).

The exposure of the plants to the diverse range of the environmental stresses affects growth and development of the plants consequently hampering the crop productivity (Farooq et al., 2011; Seki et al., 2003). Due to cold stress, horticultural crops suffer a yield loss of 10–100 %

depending upon crop and variety. In last two decades, production of apples in Himachal Pradesh has shown a decreasing trend. The global warming has been shown to affect various parameters of apples such as fruit bearing ability, less juice content, reduction in size of fruits and increased pest attack resulting in yield loss and quality of fruits. In mango, unusual or very early flowering has been experienced (Hazarika, 2013).

Water deficit is considered to be single devastating abiotic stress as compare to other environmental stress of low temperature, salinity, pH and radiations (Farooq et al., 2012; Lambers et al., 2008). It negatively influences growth and physiological parameters of the plants. The root system is greatly affected under drought stress which in turn affects the nutrient uptake and transport to the shoots (Aroca et al., 2006). Interruption of water flow inhibits cell elongation which changes morphology of the roots (Nonami, 1998). The reduction in specific root length and surface area has been observed in cauliflower, lettuce, and tomato (Agele et al., 2011; Kage et al., 2004; Schwarz et al., 1995). Oxidative damage and membrane leakage under drought stress increases which further affects the uptake of the nutrients (Reddy et al., 2004). The closure of the stomata and transpiration rate decrease are under moisture stress. Moisture stress influence each crop differently or indirectly. In soybean drought hastened flowering and physiological maturity (Desclaux and Roumet, 1996). Pervez et al. (2009) investigated the consequence of drought stress on different parameters of tomato plants.

Water deficit leads to flower shedding, reduces fruit size, fruit splitting and development of calcium deficient disorder in tomato. In eggplant, drought stress affects flowering and fruit development, reduces yield with poor color development in fruits. Flowering and fruit set shedding of flowers and young fruits, reduction in dry matter production and nutrient uptake have been observed in chilly and capsicum. In onion, splitting and doubling of bulb, poor storage life. In melons, poor fruit quality in muskmelon due to decrease in total soluble sugars, reducing sugar and ascorbic acid, increase nitrate content in watermelon fruit has been demonstrated. In leafy vegetables, toughness of leaves, poor foliage growth, accumulation of nitrates. In pea reduction in root nodulation and plant growth, poor grain fill has been observed (Bahadur et al., 2011). Zaher-Ara et al. (2016) studied the impact of drought stress on growth parameters, tissue water content and germination percentage in different citrus and reported an obvious reduction in studied parameters. Liang et al. (2020) studied the effect of drought stress on photosynthetic and physiological parameters of tomato. Shin et al. (2021) revealed decrease in growth parameters of drought-stressed lettuce seedlings (Table 1).

## 4. Biodiversity

### 4.1. Microbial diversity associated with horticultural crops

Diverse group of microbes are associated with crops and is considered important for maintaining production systems for environmental sustainability. The associated microbial communities help the plant in growth, yield improvement and adaptation to harsh environmental conditions (Verma et al., 2017). Mehta et al. (2015) reported diversity of P-solubilizers from apples and reported *Bacillus* to be the most dominant genus. Diverse groups of microbes have been reported from strawberry, mango, and banana (Dai et al., 2019; Jha et al., 2012; Sudarma and Suprpta, 2011). Walnuts and almonds have a diverse range of microbes associated with them (McGarvey et al., 2015; Tan et al., 2020; Zhang and Wang, 2017). Vegetables which make an important part of balanced diet have an important range of associated microbes. *Azotobacter* sp., *Arthrobacter woluwensis*, *Bacillus amyloliquefaciens*, *B. cereus*, *B. mycoides*, *B. paramycoides*, *B. wiedmannii*, *Flavobacterium* sp., *Micrococcus* sp., *Pae-narthrobacter nitroguajacolicus*, and *Pseudomonas* sp. have been reported from pea (Nazir et al., 2020; Osman and Yin, 2018; Sherpa et al., 2021).

On reviewing 448 bacterial and fungal species from medicinal plants, spices, plantation crops, vegetables, nuts, and fruits, it was observed that Actinobacteria, Proteobacteria, and Firmicutes were most abundant phyla and were present in all six categories of the horticultural crops. The

**Table 1.** Effect of drought stress on different horticultural crops.

Crop	Effect of drought stress	References
Almonds	Decreased germination capacity, germination rate and growth parameters	Gholami et al. (2010)
Almonds	Reduction in plant growth parameters such as fresh and dry weights of plant organs, leaf number, total leaf area, and leaf relative water content	Zokae-Khosroshahi et al. (2014)
Almonds	Reduction in seedlings growth characteristics, including total height, shoot height and shoot wet and dry weight, except root wet weight which was increased	Jahanbazy Goujani et al. (2013)
Apricot	Suppression of dry matter weight and increased starch content	Tsuchida et al. (2011)
Green bean	Decreased chlorophyll content and increased lipid peroxidation	Yasar et al. (2010)
Lettuce	Decreased growth parameters	Shin et al. (2021)
Mango	Reduction in the emergence of vegetative flushes, number of leaves per flush, flush length and weight, leaf water contents and root growth. Number of malformed panicles and percentage of malformation was minimized	Tahir et al. (2003)
Mango	Decreased relative water content and water potential and increased rate of superoxides free radical generation	Youqiang et al. (2000)
Marigold	Reduced growth vigor (i.e. plant height, shoot dry weight, flower diameter as well as its fresh and dry weights)	Asrar and Elhindi (2011)
Onion	Accumulation of proline in onion seedlings, while decreased content of chlorophyll and carotenoid	Hanci and Cebeci (2014)
Onion	Reduced the yield and increased the dry-matter percentage of the bulbs	Sorensen and Grevsen (2001)
Tomato	Decreased shoot fresh and dry weight, leaf area and relative water content, photosynthesis, starch content, Stomata and pore length	Zhou et al. (2017)
Walnut	The contents of proline and total soluble sugars increased decreased amount of starch. The levels of antioxidant activity significantly increased by POD, APX, CAT, SOD and LOX enzymes in the radicle and plumule tissues	Lotfi et al. (2019)
Walnut	Significant increases of POD especially APX isozyme activity	Lotfi et al. (2009)
Wild apricot	Decreased net photosynthetic rate, transpiration rate, stomatal conductance and relative water content of leaf	Jie et al. (2008)
Ashwagandha	Decrease in leaf area, photosynthetic pigments, root and shoot lengths and photosynthetic activity.	Kannan and Kul (2011)
Aloe vera	Impaired ability of leaves for synthesis of assimilates caused growth inhibition	Habibi (2018)

bacterial species belonging to phylum Planctomycetes were observed only in spices. On the other hand, bacterial species belonging to Nitrospirae, and Verrucomicrobia were observed only in fruits. Similarly, Mucoromycota was also observed only in case of diversity studies from fruits. Bacteroidetes and Basidiomycota were most abundant in fruits whereas Actinobacteria was most abundant in vegetables and Firmicutes in plantation crops. The fungal species belonging to phylum Ascomycota was most abundant in medicinal plants. Among 448 bacterial and fungal species, banana, and cucumber showed highest diversity followed by tea, grapes and ashwagandha. The species belonging to genera *Pseudomonas* and *Bacillus* were most abundant and present in fruits, vegetables, spices, plantation crops, nuts and medicinal plants. The genera *Akkermansia*, *Mortierella*, and *Nitrospira* could be observed only in fruits whereas *Pir-ellula* could be observed only in garlic (Figure 2; Figure 3).

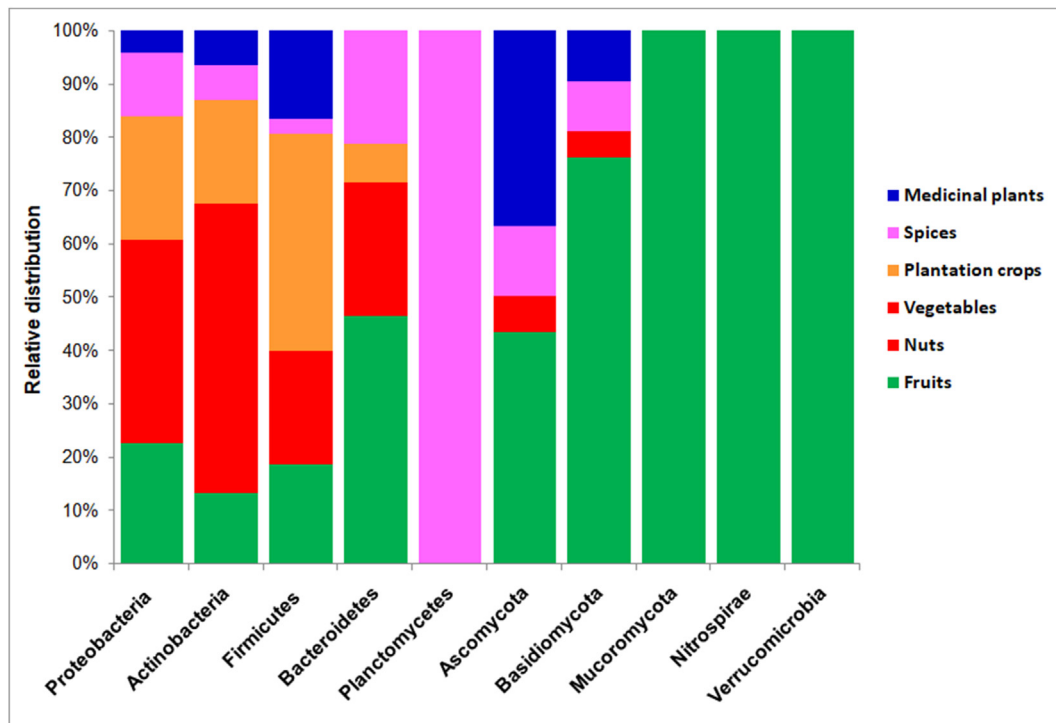


Figure 2. Relative distribution of various phyla from different horticultural crops.

#### 4.2. Biodiversity of drought adaptive microbes associated with horticulture crops

Drought adaptive microbes have a potential role in mitigating the adverse effects of the drought stress in plants. These microbes with different mechanisms ensure the survival of the plants under water deficit conditions. Drought adaptive microbes have been reported from a wide range of crops. The microbial diversity with different PGP attributes from the stressed environments can be isolated and used as bioinoculants for plants under conditions of abiotic stress to promote growth. On reviewing diverse drought adaptive microbes and their phylogenetic profiling revealed Proteobacteria to be the dominant phylum of drought adaptive microbes. Proteobacteria consisted of nineteen species belonging to diverse genera including *Achromobacter*, *Acinetobacter*, *Azotobacter*, *Burkholderia*, *Citrobacter*, *Ensifer*, *Ochrobactrum*, *Pseudomonas*, *Rhizobium*, *Serratia*, *Sinorhizobium* and *Variovorax*. Firmicutes consisted of drought adaptive *Bacillus amyloliquefaciens*, *B. licheniformis*, *B. methylotrophicus*, *B. pumilus*, *B. subtilis* and *Paenibacillus polymyxa*. Actinobacteria revealed species of four diverse genera viz, *Arthrobacter*, *Citricoccus*, *Microbacterium* and *Streptomyces*. Drought adaptive fungal species belong to five different genera including *Aspergillus*, *Glomus*, *Phoma*, *Penicillium*, and *Rhizophagus* (Figure 4).

#### 5. Role of drought adaptive microbes for mitigation of drought stress in horticultural crops

The framing of the green policies and shift towards sustainable development has become one of the major challenges globally. In this regard, the use of the stress adaptive microbes in agricultural sector is on rise. Stress adaptive microbes are the potential bioresources as bioinoculants for combating abiotic as well as the biotic stress management.

##### 5.1. 1-aminocyclopropane-1-carboxylate deaminase

Ethylene is the gaseous plant hormone that facilitates several aspects of plant's normal growth and development. Under the drought conditions the concentration of hormone increases and it hinders the plant growth

by inhibiting the development of roots, nodulation in legume forming plants, chlorophyll destruction and promotion of epinastic movements in aerial plant parts (Ravanbakhsh et al., 2018). A pyridoxal phosphate dependent and multimeric enzyme, 1-aminocyclopropane-1-carboxylate (ACC) deaminase is known for alleviating the harmful effect of ethylene which is a natural phytohormone generated in the response of drought stress. ACC deaminase enzyme has a molecular mass of 35–42 kDa and is produced by all realm of cellular life i.e. Archaea, Bacteria and Eukarya (Gamalero et al., 2017; Gupta and Pandey, 2019). The microbial ACC deaminase lowers the ethylene level in plant by hydrolyzing drought stress synthesized ACC in plants to  $\alpha$ -ketobutyrate and ammonia, which ultimately reduces the stress triggered ethylene (Glick et al., 2007).

In horticulture crops, the increased level of ripening hormone, ethylene is lowered by the various drought tolerant microbes. In a study, ACC deaminase activity exhibiting bacterium *Achromobacter piechaudii* was reported for conferring the water deficit stress tolerance in the two horticulture crops i.e. tomato and pepper (Mayak et al., 2004). An investigation of Arshad et al. (2008) reported *Pseudomonas* sp. for exhibiting ACC deaminase activity and eliminates the deleterious effect of drought in pea plant and promoting growth, yield and ripening as compared to uninoculated control. Sharp et al. (2011) reported ACC deaminase producing rhizobacterium *Variovorax paradoxus* for effectively reducing ethylene concentration and drought stress in *Cytisus × praecox*. In another report, drought tolerant bacterial species, *Bacillus subtilis*, *Ensifer meliloti*, and *Rhizophagus irregularis* were reported for exhibiting ACC deaminase activity. These strains were reported for alleviating drought stress in fenugreek plant upon inoculation as compared to uninoculated control (Barnawal et al., 2013).

*Bacillus subtilis* isolated from seeds of tomato plant was reported for producing ACC deaminase, indole-3-actic acid (IAA), solubilization of phosphorus, production of siderophores and fixing nitrogen. This strain of bacterial species was reported for enhancing the growth tomato seedlings upon inoculation under gnotobiotic and greenhouse conditions (Xu et al., 2014). The osmotolerant actinobacterium, *Citricoccus zhaicaiensis* was reported for exhibiting ACC deaminase along with multitudinous growth enhancing traits including production of IAA, gibberellins and ammonia; solubilization of phosphorus and zinc. The inoculation of

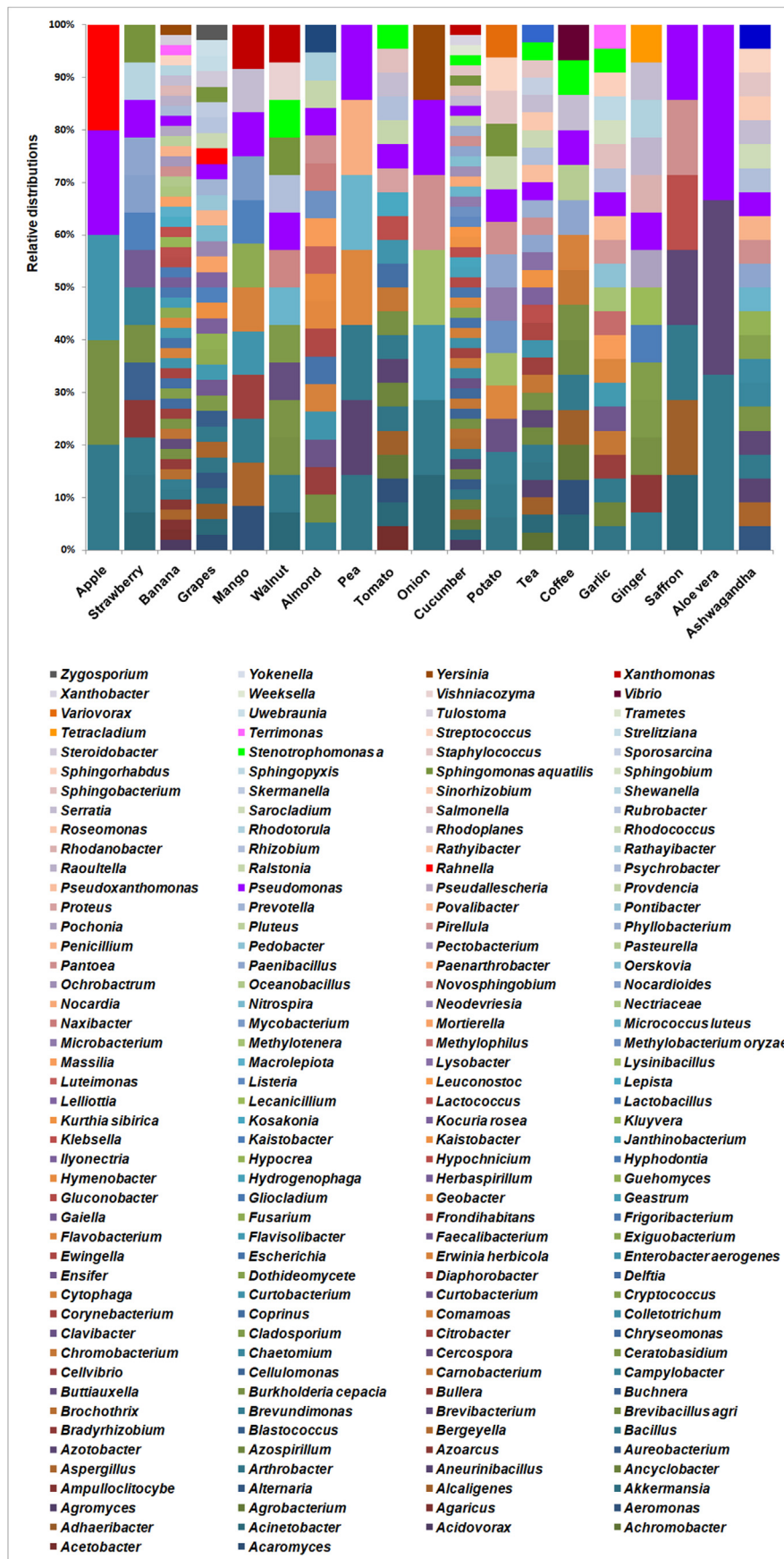


Figure 3. Relative distribution of various genera from different horticultural crops.

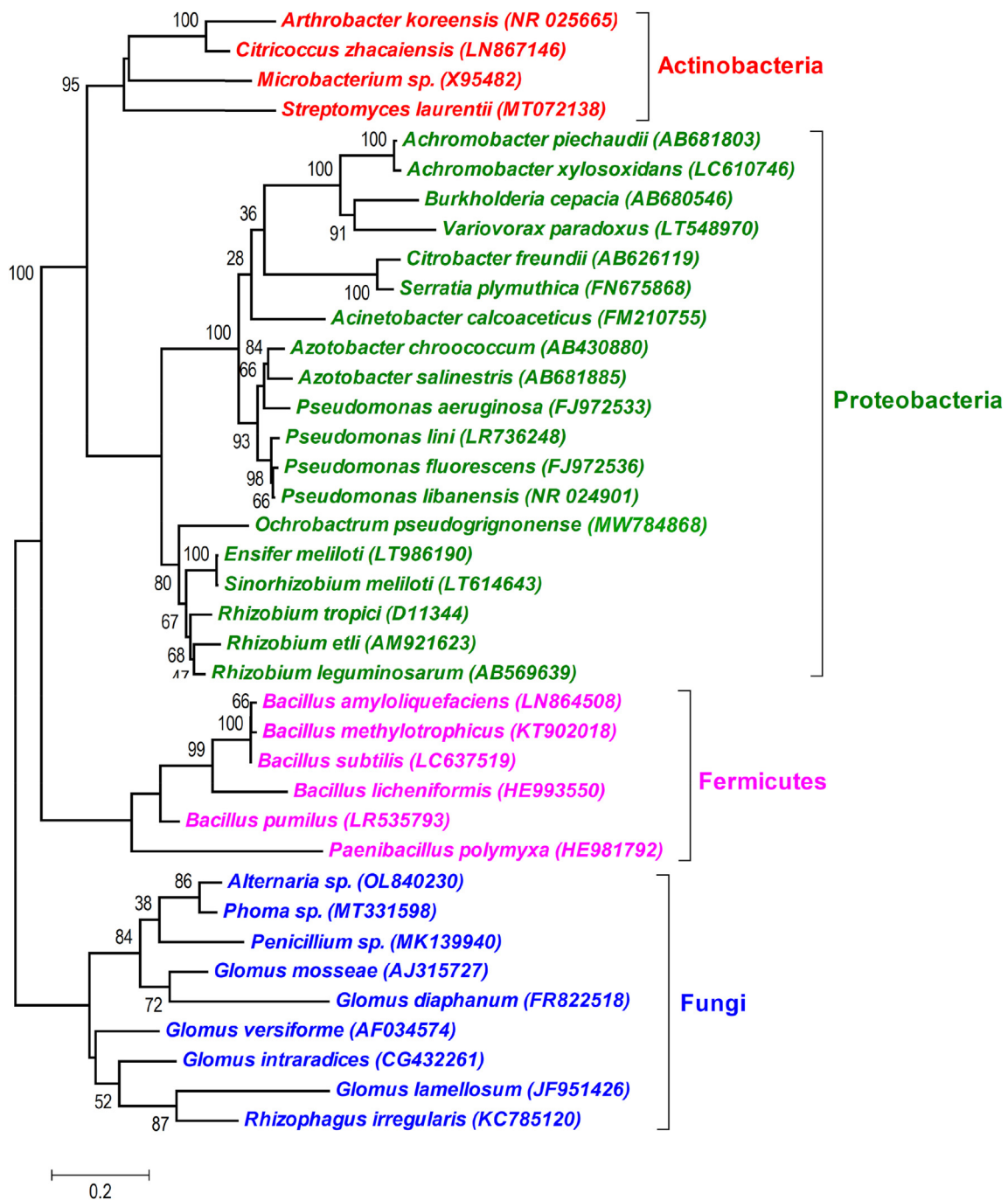


Figure 4. Phylogenetic profiling of drought adaptive microbes.

this strain in the onion seeds sown under drought stressed conditions were reported for improving the germination rate and seedling vigour (Selvakumar et al., 2015). In an investigation, *Citrobacter freundii*, a drought tolerant and ACC deaminase producing rhizobacterium was reported alleviating the water deficit stress in tomato crop (Ullah et al., 2016). In another study, three bacterial species *Burkholderia cepacia*, *Citrobacter freundii*, and *Serratia marcescens* were reported for producing ACC deaminase activity. These bacterial species were reported as tolerant to drought as well as saline stress conditions. The treatments of capsicum with these strains were alleviating the stress of water deficit and salinity and enhance the plant growth (Maxton et al., 2018).

In an another report, *Rhizobium leguminosarum* has been found to produce ACC deaminase and tolerate drought and heavy metals (cadmium) stress. The inoculation with this nitrogen fixing bacterium in pea plant

helped in combating drought and cadmium stress (Belimov et al., 2019). In another report, desert cactus (*Euphorbia trigona*) bacterial endophytes *Bacillus amyloliquefaciens* was reported for de-stressing the moisture stress in tomato upon inoculation of the strain (Eke et al., 2019). In a similar study, *Bacillus* strains isolated from *Cistanthe longiscapa* rhizosphere, the native desert plant. The strain was reported for producing ethylene reducing enzyme, ACC deaminase, IAA, and exopolysaccharides and solubilizes phosphorus. The strain inoculation in tomato seeds and seedlings were reported for conferring the water scarcity (Astorga-Eló et al., 2021).

### 5.2. Osmotic adjustments

Water level in plant is crucial of their survival under the water deficit stress. Plants maintain the higher water by the osmotic adjustment in

response to water deficit stress. Osmotic adjustment helps in guarding the enzymes, cellular organelles, proteins and membranes from oxidative damage (Huang et al., 2014). In osmotic adjustment organic and inorganic solutes i.e. compatible solutes gets actively accumulated during the moisture stress, which helps in the maintaining the cellular turgor and helps the plant in lowering water potential without decreasing actual content of water (Kiani et al., 2007; Serraj and Sinclair, 2002). There are different solutes namely, glycine betaine, sugar, organic acids, poly-ols, inorganic ions and non-amino protein acid i.e. proline (Farooq et al., 2008; Ngumbi and Kloepper, 2016). Drought tolerant microbe's inoculation in the drought conditions plays a key role in maintaining the cell turgor through osmotic adjustment. Asrar et al. (2012) reported the inoculation of *Glomus deserticola* fungi in snapdragon flower grown under water stressed conditions was enhancing the proline content in comparison with untreated flower. In a study, drought stressed mung bean treated with drought tolerant microbes *Pseudomonas aeruginosa* was reported for increasing the cellular osmolytes and relative water content (Sarma and Saikia, 2014). In a report, the inoculation with consortium of *Rhizophagus* sp. and *Burkholderia seminalis* in tomato and bell pepper was reported for increasing accumulation of proline and mitigates the drought stress in the plants (Tallapragada et al., 2016).

In a study, AMF (*Glomus intraradices* and *G. mosseae*) were inoculated in water stressed fennel which results in the increasing the proline content in the plant as compared to untreated plant (Zardak et al., 2018). Khan et al. (2019) investigated microbial consortium containing rhizobacteria namely, *Bacillus subtilis*, *B. thuringiensis* and *B. megaterium* in drought stressed chickpea. The inoculation of microbial consortium resulted in the enhancement of compatible solutes including proline, L-histidine, L-isoleucine, L-arginine, and tryptophan. In another report, the combination of *Glomus mosseae*, *G. etunicatum*, *Azotobacter chroococcum* and *Azospirillum lipofrum* in walnut exposed to drought stress was reported for alleviating water deficit stress by increasing proline level and soluble sugar content (Behrooz et al., 2019). Abbasi et al. (2020) reported *Streptomyces* for alleviating the drought stress in tomato crop upon inoculation by increasing the proline and total sugar content in the plant. In an investigation, inoculation drought tolerant bacterium, *Bacillus subtilis* in drought stressed okra, was reported for increasing compatible solutes including total sugar and proline which helps to resist the stress (Puthiyottil and Akkara, 2021).

### 5.3. Production of phytohormones

Modification of phytohormones activity in the plant is another mechanism to alleviate the drought in the horticultural crops. Plants produce different kind of phytohormones such as auxin (indole-3-acetic acid), ethylene, abscisic acid, jasmonic acid, gibberellins, and cytokinins that plays imperative role in the plant growth, development and abiotic stress tolerance (Kaur et al., 2021b; Tiwari et al., 2020). Drought tolerant microbiomes help in producing these phytohormones that cope up with water deficit conditions (Vurukonda et al., 2016). Different microbes have been found to produce various phytohormones which help in alleviating drought stress in horticulture crops. In a report, the drought stress was de-stressed in the common bean by two drought tolerant and phytohormones such as abscisic acid, indole-3-acetic acid and gibberellins producing microbes namely, *Rhizobium tropici* and *Paenibacillus polymyxa* (Figueiredo et al., 2008). In a study, *Bacillus pumilus* and *Achromobacter xylosoxidans* the endophytic bacteria isolated from sunflower was reported for producing phytohormones jasmonic acid and salicylic acid that helps in the enhancing growth of water stressed sunflower seedlings (Forchetti et al., 2010). Benabdellah et al. (2011) reported the microbial blend of *Bacillus* sp. and *Glomus* sp. was alleviating the drought stress in the spice, *Trifolium repens* via producing IAA phytohormone.

In an investigation, strawberries growing under drought condition were inoculation with IAA producing rhizobacterium *Paenibacillus polymyxa* which was reported for mitigating the drought stress in the fruit and improves its growth (Erdogan et al., 2016). Cherni et al. (2019)

isolated IAA producing rhizospheric microbiota *Ensifer adhaerens* and *Pseudomonas resinovorans* associated with *Citrus sinensis*. These microbes reported for alleviating stress caused by water shortage in tomato as well as capsicum. In a study, drought tolerant bacteria *Pseudomonas lini* and *Serratia plymuthica* were reported for the production IAA along with abscisic acid and their microbial blend inoculation in the water stressed jujube seedling which ameliorated the drought stress (Zhang et al., 2020). Under low moisture content microbial consortium (*Mesorhizobium ciceri*, *B. subtilis*, and *B. mojavensis*) containing IAA solubilizer and ACC deaminase activity exhibiting microbes was reported for de-stressing water stress in chickpea plant (Mahmood Aulakh et al., 2020). In a study, *Bacillus* sp., and *Enterobacter* sp. having ability to tolerate drought and produce IAA and ACC deaminase was reported for alleviating drought stress in velvet bean upon inoculation (Saleem et al., 2018).

### 5.4. Nutrient acquisition

Drought stress affects the nutrient availability in the soil, nutrient uptake by the roots as well as the transport of nutrients from root to shoot (Bagheri et al., 2018; Goicoechea et al., 1997). The reduced uptake is attributed to the fact that under drought stress transpiration rates are restricted and active transport as well as membrane permeability is impaired (Alam, 1999; Hu and Schmidhalter, 2005). The deficiency of the macronutrients and micronutrients then limits growth and productivity of the crops.

Nitrogen is vital mineral element required in large amounts and is a constituent of amino and nucleic acids (Hu and Schmidhalter, 2005; Rana et al., 2020). Hence the deficiency rapidly inhibits plant growth. The study of Smika et al. (1965) defined relationship between water availability and the N-fertilizer responses and concluded that N fertilizer will not increase the yield of the crops until the water is available in sufficient amounts. *Lactuca sativa* showed decreased N content in plants, dry weight when imposed drought stress (−0.17 MPa) (Ruiz-Lozano and Azcón, 1996). *Vigna unguiculata* showed decrease in shoot biomass, nitrate reductase activity and increase in nitrate content in the roots under water stress caused (Silveira et al., 2001).

Phosphorus (P) is a vital macronutrient with role in metabolic activities and root development (Kour et al., 2021). The deficiency of P reduces leaf expansion, leaf area, number of leaves, and shoot/root ratio. Phosphorus deficiency delays flower initiation, decreases the number of flowers and restricts seed formation. Premature senescence of leaves is another factor limiting seed yield in P-deficient plants (Rouphael et al., 2012; Yadav 2022). The reduced content of P in vegetables directly affects its nutritional quality. It diminishes the contribution of vegetables to the total P dietary intake as fruits and vegetables contribute to about 11% of the total P dietary intake (Levander, 1990). P is acquired from soil solution in a form of phosphate anions (Raghothama and Karthikeyan, 2005; Schachtman et al., 1998; Vitousek et al., 2009). Diffusional cross-sections and P diffusion coefficients have been revealed to decline with soil desiccation, which results in size reduction of the root zones from which P can be taken up (Gahoonia et al., 1994). Drought limits the availability of P in dry soils even more (Püschel et al., 2021).

Potassium (K) is an essential nutrient in protein synthesis, glycolytic enzymes, and photosynthesis (Kaur et al., 2021a,b; Kour et al., 2020). It is an important osmoticum that mediates cell expansion and turgor-driven movements. The decreasing soil water content decreases the availability of K<sup>+</sup> ions to the plant due to the decreasing mobility of K<sup>+</sup> ions under stress conditions. The study of Kuchenbuch et al. (1986) showed that low levels of soil moisture reduced root growth and the rate of potassium inflow in onion plants. Numerous genes and regulating pathways have been identified which reveal the processes by which plants react to low amounts of N, P, and K. On the contrary, it has been demonstrated that out of approximately 2,200 differentially expressed genes of sorghum, no nutrient transporter genes has been reported to respond to dehydration (Buchanan et al., 2005).



The role of drought adaptive microbes is incredible in mitigation of drought stress in horticulture and is increasing day by day. These microbiomes exhibit a range of mechanisms to support their hosts under stressful environment. Asrar and Elhindi (2011) reported improved growth, pigments, and P-content and flower quality in marigold under drought stress with AMF. Ullah et al. (2016) reported alleviation of drought stress in tomato in combined treatment of silicon and plant growth promoting rhizobacteria (PGPR) by increased  $\text{Ca}^{2+}$ ,  $\text{K}^+$  and  $\text{Mg}^{2+}$  accumulation, relative water content and decreased electrolyte leakage.

### 5.5. Antioxidant defence

Drought stress disrupts photosynthetic machinery and increase the rate of photorespiration which alters the normal homeostasis of plant cells and results in overproduction of reactive oxygen species (ROS). To scavenge ROS, plants are naturally gifted with antioxidant defense system to protect the cells from the oxidative damage under water stress conditions (Kaushal and Wani, 2016; Miller et al., 2010). PGP microbes exhibiting antioxidant defense mechanisms under stressed environment provide additional support to plants in scavenging ROS. Many studies have reported the mitigation of water deficit in different horticultural crops with inoculation of PGP microbes and antioxidant defense as one of the mechanisms. Amiri et al. (2015) reported the alleviation of drought stress in *Pelargonium graveolens* by activities of antioxidant defense and secondary metabolites by AMF inoculation. Tallapragada et al. (2016) investigated the role of *Rhizophagus fasciculatum* and *R. intraradices* as well as *Burkholderia seminalis* on growth of tomato and bell pepper growth under drought stress. Catalase and guaiacol peroxidase activities were observed to be one of the mechanisms of stress alleviation. Chiappero et al. (2019) reported the potential of alleviating the adverse effects of drought stress and plant growth promotion in *Mentha piperita* with *Bacillus amyloliquefaciens* and *Pseudomonas fluorescens* through improved antioxidant status. Thus, utilizing the capabilities of PGP microbes for drought stress mitigation is an efficient approach for sustainable agriculture.

## 6. Molecular mechanisms involved in drought stress tolerance

Gene expression studies are a powerful tool for complete understanding of holistic responses of an organism to their environment (Schlauch et al., 2010). A comprehensive understanding of transcriptomic alterations in response to presence of the environmental stress is important. The exposure of the plants to abiotic stress triggers various molecular and physiological changes in plants such as quick transcriptomic and metabolic adjustments, reduction of leaf turgor pressure and osmotic potential adjustments (Tardieu et al., 2014). Gene expression belonging to different functional and regulatory groups shows alterations in response to environmental stress (Bashir et al., 2019). Functional group products include detoxifying enzymes, osmoprotectants, key enzymes for osmolyte biosynthesis and ROS scavengers whereas regulatory group regulate the expression of others gene in response to drought stress such as transcription factors, protein phosphatases and kinases (Ali et al., 2017). *Helianthus annuus* showed 805 and 198 differentially expressed genes in leaves and roots, respectively and another 71 genes were differentially expressed in both organs, in which more genes were up-regulated under drought stress (Liang et al., 2017).

Stress adaptive microbes have been observed to impact host at molecular levels while imparting drought stress tolerance. The study of (Lim and Kim, 2013) identified six differentially expressed stress proteins in *Bacillus licheniformis* treated pepper plants and exposed to water stress. Among stress proteins, specific genes *Cadh*, *VA*, *sHSP* and *CaPR-10* showed 1.5 fold expressions in treated pepper plants. The whole-transcriptomic sequencing of *Burkholderia phytofirmans* revealed a wide range of the activities encoded in genome of the strain including the up regulation of transcripts in response to plant drought stress were majorly involved in cellular homeostasis and detoxification of ROS

(Sheibani-Tezerji et al., 2015). *Arabidopsis thaliana* inoculated with *Paenibacillus yonginensis* showed up regulation of *AtERD15*, *AtRAB18* and *AtLT178* genes under drought stress (Sukweenadhi et al., 2015). The up regulation of genes viz *DREB/EREB* for transcription factors, *P5CS*, *GOLS* for osmoprotectants, and *PIP* and *TIP* for water transporter has been observed under drought stress in soybean plants inoculated with *Pseudomonas simiae* (Vaishnav and Choudhary, 2019).

## 7. Biotechnological applications of drought adaptive-microbes

### 7.1. Biofertilizers

Drought is one of the most significant barriers to boosting crop growth and productivity in a number of regions of the world (Naveed et al., 2014). Drought is also one of the most important abiotic elements that have a negative impact on crops yield. Water scarcity is one of the crop production restricting factors and a danger to crop production success (Fathi and Tari, 2016). Fruits, vegetables, decorative, medicinal, plantation, and aromatic plants are the most common horticultural crops. These crops play an important role in the country's agriculture and economy. Considering the significance of horticulture crops in terms of food and nutrition security, they have lagged behind other food-grain crops in terms of improvement. Current global climate patterns have resulted in an increase in atmospheric carbon dioxide content, which has led in an increase in global average temperature. Extreme weather conditions such as drought, heat stress, and high salinity are severe challenges for horticultural crops today, and can limit and delay crop harvest by up to 70%, leading to a huge cost on quality and productivity of product, as well as a significant loss in farm income. Drought frequency has increased as a result of global warming in recent decades, affecting many crucial crop growth stages like reproduction, flowering, fruit ripening, bulb maturity, and fruit development, resulting in a 10–87% crop yield drop in horticulture crops.

Several management solutions have proven to be effective in ensuring the quality and product of horticulture crops during droughts. Partial root-zone drying (PRD) and regulated deficit irrigation (RDI) are two water-management approaches that have been successfully demonstrated and have resulted in considerable increases in horticultural produce quality and yield. However, both RDI and PRD irrigation approaches necessitate advanced management skills as well as exact soil-water content monitoring, which is only attainable with drip and other types of automated micro-irrigation systems. Mulching, compartmental bonding, basin listing, and other water-management strategies are examples. Aside from these strategies, other management strategies include crop, variety, and rootstock selection, all of which play a key role in drought tolerance. To facilitate the plant productivity and growth under drought stress, biofertilizers can be used in the soil.

Biofertilizers are microbial inoculants that contain the culture of dormant or active cells of N-fixing, P-solubilizing/mobilizing, and K-solubilizing effective strains (Fasusi et al., 2021). They have been demonstrated to increase the plant's yield and growth by 10–40% (Kawalekar, 2013). They not only work by adding nutrients to the soil to boosting up the soil fertility and crop productivity, but they also play an amazing role in protecting the plant against diseases and pests. They have been demonstrated to improve root system growth, extend root system life, destroy hazardous compounds, promote seedling survival, and shorten flowering time (Youssef and Eissa, 2014). Biofertilizers have been categorized based on their roles and modes of action. Nitrogen fixer (N-fixer), phosphorus solubilizer (P-solubilizer), potassium solubilizer (K-solubilizer), and plant growth promoting rhizobacteria (PGPR) are the most regularly utilized biofertilizers (Fasusi et al., 2021; Mahdi et al., 2010). Drought-tolerant microorganisms have been chosen from various sources and used as microbial strains, microbial consortiums, biofertilizers, and biocontrol agents to substitute chemical fertilizers as environmentally friendly resources for plant growth promotion and drought stress alleviation (Kour et al., 2019) (Table 2).

**Table 2.** Drought adaptive microbes as biofertilizers for various horticulture crops.

Drought adoptive microbes	Horticulture crop	Reference
<i>Achromobacter xylosoxidans</i>	<i>Solanum tuberosum</i>	Belimov et al. (2015)
<i>Alternaria</i> sp.	<i>Solanum lycopersicum</i>	Azad and Kaminskyj (2016)
<i>Arthrobacter koreensis</i>	<i>Capsicum annuum</i>	Vilchez et al. (2016)
<i>Arthrobacter piechaudii</i>	<i>Capsicum annuum</i>	Vilchez et al. (2016)
<i>Azotobacter chroococcum</i>	<i>Mentha pulegium</i>	Asghari et al. (2020)
<i>Bacillus licheniformis</i>	<i>Capsicum annuum</i>	Lim and Kim (2013)
<i>Bacillus pumilus</i>	<i>Glycyrrhiza uralensis</i>	Xie et al. (2019)
<i>Bacillus</i> sp.	<i>Lactuca sativa</i>	Arkhipova et al. (2007)
<i>Bacillus</i> sp.	<i>Capsicum annuum</i>	Marasco et al. (2012)
<i>Bacillus</i> sp.	<i>Solanum lycopersicum</i>	La Fua et al. (2021)
<i>Bacillus subtilis</i>	<i>Pisum sativum</i>	Saikia et al. (2018)
<i>Bacillus subtilis</i>	<i>Trigonella foenum-graecum</i>	Barnawal et al. (2013)
<i>Ensifer meliloti</i>	<i>Trigonella foenum-graecum</i>	Barnawal et al. (2013)
<i>Glomus diaphanum</i>	<i>Poncirus trifoliata</i>	Wu et al. (2008)
<i>Glomus intraradices</i>	<i>Lycopersicon esculentum</i>	Subramanian et al. (2006)
<i>Glomus moseseae</i>	<i>Fragaria x ananassa</i>	Yin et al. (2010)
<i>Glomus lamellosum</i>	<i>Cinnamomum migao</i>	Liao et al. (2021)
<i>Glomus mosseae</i>	<i>Poncirus trifoliata</i>	Wu et al. (2008)
<i>Glomus versiforme</i>	<i>Poncirus trifoliata</i>	Wu et al. (2008)
<i>Microbacterium</i> sp.	<i>Capsicum annuum</i>	Vilchez et al. (2016)
<i>Ochrobactrum pseudogrignonense</i>	<i>Pisum sativum</i>	Saikia et al. (2018)
<i>Phoma</i> sp.	<i>Pinus tabulaeformis</i>	Bae et al. (2009)
<i>Pseudomonas oxytuberosa</i>	<i>Solanum tuberosum</i>	Belimov et al. (2015)
<i>Pseudomonas</i> sp.	<i>Solanum lycopersicum</i>	La Fua et al. (2021)
<i>Pseudomonas</i> sp.	<i>Pisum sativum</i>	Saikia et al. (2018)
<i>Rhizobium etli</i>	<i>Phaseolus vulgaris</i>	Reina-Bueno et al. (2012)
<i>Rhizopagus irregularis</i>	<i>Trigonella foenum-graecum</i>	Barnawal et al. (2013)
<i>Sinorhizobium meliloti</i>	<i>Medicago sativa</i> L.	Xu et al. (2012)
<i>Variovorax paradoxus</i>	<i>Solanum tuberosum</i>	Belimov et al. (2015)
<i>Variovorax</i> sp.	<i>Brassica oleracea</i>	Kim et al. (2020)

## 7.2. Biopesticides

One of major concern of growing world population is food security. It is of critical importance due to the fact that not only the well-being of human but also the global economics depends on steady and dependable food supply. Steadily growing world population constantly increases the pressure on global food security. To have a stable and reliable food security it's important to increase our agricultural output and minimize the loss of crops due to pests. Initially, the use of chemical pesticides has reduced the crop loss due to pests but their prolonged and excessive use has led to many environmental issues like environmental pollution (soil pollution), negative effect on human and animal health due to their residual presence in food, decreased biodiversity, resistance development in insects, secondary pests outbreaks which are normally controlled by their natural predators (Vega and Kaya, 2012).

As biopesticides are naturally occurring i.e. they are derived from plants, animals, minerals or microorganism. They are also target specific and do not leave hazardous residual in trail. An additional advantage of use of microbial pesticide is its replication in host due to genetic transmission between organisms resulting in long term effectiveness in controlling the pest population without the need of repetitive application. Since these biopesticides are evidently safer for both user and the environment and are more sustainable than chemical pesticides their use as an alternative for chemical pesticides in Integrated Pest Management (IPM) is of budding interest. These biopesticides are a key ingredient of

sustainable farming because of they help in maximizing the fertility of soil because they are non-toxic and environmental friendly (Thakur et al., 2020). Thus the use of biopesticides seems to be poised with growing times.

Biological pesticides or biopesticides can be simply defined as pesticides derived from any available biological sources like microbes, plants and animals. According to US EPA (US Environmental Protection Agency) biopesticides include biochemical pesticides (pests controlling naturally occurring substances), microbial pesticides (pests controlling microbes), and plant incorporated protectants or PIPs (Sporleder and Lacey, 2013). Historically the term biopesticides is associated with biological pest control by the manipulation of living organisms. It includes several types of interventions of pest control like parasitic, chemical interactions or predatory. Thus the term biopesticides can be concise as several natural, biologically active substances which have inhibitory effects on pests and crop diseases. Broadly biopesticides are classified into following three categories, Microbial pesticides, plant incorporated protectants and biochemical pesticides (Sporleder and Lacey, 2013).

Drought is an environmental factor that is of interest. It has been shown to have an impact on crop output and quality in a variety of plants (Salehi-Lisar and Bakhshayeshan-Agdam, 2016). Drought is anticipated to cause a huge damage on plant development in more than half of the world's arable lands by 2050 (Kasim et al., 2013). Interestingly, few bacterial species showed dual plant benefit traits, both growth promotion and stress protection, such as *Bacillus methylotrophicus* CSY-F1 produces plant growth-promoting compounds and ameliorates drought stress in cucumber (*Cucumis sativus*) growing in high-ferulic-acid soil (Hou et al., 2018). The most suitable option for the future of modern horticulture appears to be the effective use of biopreparations in conventional crops, rather than confining their use to a small number of ecological or organic agricultural crops.

Seed treatment has a number of advantages for controlling pathogenic fungus and is a possible alternative to industrial pesticides. *Fusarium* species, particularly *Fusarium verticillioides*, are also reported to be controlled by endophytic *Bacillus* inoculants (Roberts et al., 1994; Snook et al., 2009). The *B. mojavensis* strain obtained from the rhizosphere of soybean plants was an antagonistic strain that efficiently controlled *Rhizoctonia solani*, a pathogenic fungus that causes massive horticulture crop harvest losses (Moussa, 2002). El Tarabily et al. (2008) used endophytic actinomycetes to promote and biologically regulate seedlings and mature plants of *C. sativus* (*Streptomyces spiralis*, *Actinoplanes campanulatus*, and *Micromonospora chalcone*). *Pythium aphanidermatum* (a soil-borne pathogen that produces oospores) causes cucumber seedling and root infections, causing harm to horticulture crops. Actinomycetes colonize the roots of injected plants, promoting their growth and reducing the influence of *P. aphanidermatum*, according to this experiment. The investigation further evaluated the influence of Actinomycetes with that of a chemical fungicide (metalaxyl) and showed that fungicide could be replaced with plant inoculation with endophytic Actinomycetes. *B. aryabhatai* screened from soil under heavy use of chemicals, could be very advantageous as a bioremediation agent in paraquat-contaminated sites (Inthama et al., 2021).

Drought adaptive microorganisms therefore offer a lot of potential as biofertilizers and biopesticides. Despite our limited understanding of the mechanisms of action of diverse microbes, studies on the impact of drought stress on horticultural crops have revealed that the application of different microbes allows for effective plant protection. Biopreparations should be multicomponent due to the considerable variability of the environment in order to produce optimal degrees of microorganism cooperation and the end desired effect. Combining fungal and bacterial strains into a single formulation improves effectiveness and reliability, allowing for greater crop specificity, and appears to be highly promising.

## 8. Conclusions

The growth and development of the plants is adversely affected by nature wrath in the form of the scarcity of water. Water deficit is

significant in areas where agriculture is majorly rainfed and is in fact dangerous for humanity as well as nature. It results in high economic losses especially in arid and semi-arid regions. Inoculation of the horticultural crops with drought stress adaptive and PGP microbes is an efficient approach for water retention and improving drought tolerance. The genomic studies including identification, cloning and functional characterization of genes in stress adaptive microbes that provide resistance under drought stress could be carried out. In future, with the approaches of system biology studies can be focused on how stress adaptive microbiomes alter metabolic profiling under water deficit. The most important is to untie the complexity of the genetic networks and metabolic-interacting events which are actually responsible for plant-microbe interactions under stressed environment.

## Declarations

### Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

### Funding statement

This work was supported by the Department of Environment, Science & Technology (DEST), Shimla, Himachal Pradesh, India funded project "Development of Microbial Consortium as Bio-inoculants for Drought and Low Temperature Growing Crops for Organic Farming in Himachal Pradesh".

### Data availability statement

No data was used for the research described in the article.

### Declaration of interests statement

The authors declare no conflict of interest.

### Additional information

No additional information is available for this paper.

## References

- Abbasi, S., Sadeghi, A., Safaie, N., 2020. *Streptomyces* alleviate drought stress in tomato plants and modulate the expression of transcription factors ERF1 and WRKY70 genes. *Sci. Hortic.* 265, 109206.
- Adhikari, S., 2018. Drought impact and adaptation strategies in the mid-hill farming system of western Nepal. *Environments* 5 (9), 101.
- Adnan, S., 1993. Living without Floods. Dhaka, Bangladesh. Research & Advisory Services.
- Agele, S., Iremiren, G., Ojeniyi, S., 2011. Evapotranspiration, water use efficiency and yield of rainfed and irrigated tomato. *Int. J. Agric. Biol.* 13 (4), 1–8.
- Alam, S.M., 1999. Nutrient uptake by plants under stress conditions. *Handbook of Plant and Crop Stress* 2, 285–313.
- Ali, F., Bano, A., Fazal, A., 2017. Recent methods of drought stress tolerance in plants. *Plant Growth Regul.* 82 (3), 363–375.
- Amiri, R., Nikbakht, A., Etemadi, N., 2015. Alleviation of drought stress on rose geranium [*Pelargonium graveolens* (L.) Herit.] in terms of antioxidant activity and secondary metabolites by mycorrhizal inoculation. *Sci. Hortic.* 197, 373–380.
- Ansari, F.A., Ahmad, I., 2019. Alleviating drought stress of crops through PGPR: mechanism and application. In: Singh, D.P., Gupta, V.K., Prabha, R. (Eds.), *Microbial Interventions in Agriculture and Environment: Volume 2: Rhizosphere, Microbiome and Agro-Ecology*. Springer Singapore, Singapore, pp. 341–358.
- Arkhipova, T., Prinsen, E., Veselov, S., Martinenko, E., Melentiev, A., Kudoyarova, G., 2007. Cytokinin producing bacteria enhance plant growth in drying soil. *Plant Soil* 292 (1), 305–315.
- Aroca, R., Ferrante, A., Vernieri, P., Chrispeels, M.J., 2006. Drought, abscisic acid and transpiration rate effects on the regulation of PIP aquaporin gene expression and abundance in *Phaseolus vulgaris* plants. *Ann. Bot.* 98 (6), 1301–1310.
- Arshad, M., Shaharouna, B., Mahmood, T., 2008. Inoculation with *Pseudomonas* spp. containing ACC-Deaminase partially eliminates the effects of drought stress on growth, yield, and ripening of pea (*Pisum sativum* L.). *Pedosphere* 18 (5), 611–620.
- Asghari, B., Khademian, R., Sedaghati, B., 2020. Plant growth promoting rhizobacteria (PGPR) confer drought resistance and stimulate biosynthesis of secondary metabolites in pennyroyal (*Mentha pulegium* L.) under water shortage condition. *Sci. Hortic.* 263, 109132.
- Asrar, A.A., Abdel-Fattah, G.M., Elhindi, K.M., 2012. Improving growth, flower yield, and water relations of snapdragon (*Antirrhinum majus* L.) plants grown under well-watered and water-stress conditions using arbuscular mycorrhizal fungi. *Photosynthetica* 50 (2), 305–316.
- Asrar, A.-W.A., Elhindi, K.M., 2011. Alleviation of drought stress of marigold (*Tagetes erecta*) plants by using arbuscular mycorrhizal fungi. *Saudi J. Biol. Sci.* 18 (1), 93–98.
- Astorga-Eló, M., Gonzalez, S., Acuña, J.J., Sadowsky, M.J., Jorquera, M.A., 2021. Rhizobacteria from 'flowering desert' events contribute to the mitigation of water scarcity stress during tomato seedling germination and growth. *Sci. Rep.* 11 (1), 13745.
- Azad, K., Kaminskyj, S., 2016. A fungal endophyte strategy for mitigating the effect of salt and drought stress on plant growth. *Symbiosis* 68 (1–3), 73–78.
- Bae, H., Sicher, R.C., Kim, M.S., Kim, S.-H., Strem, M.D., Melnick, R.L., Bailey, B.A., 2009. The beneficial endophyte *Trichoderma hamatum* isolate DIS 219b promotes growth and delays the onset of the drought response in *Theobroma cacao*. *J. Exp. Bot.* 60 (11), 3279–3295.
- Bagheri, V., Shamshiri, M., Shirani, H., Roosta, H., 2018. Nutrient Uptake and Distribution in Mycorrhizal Pistachio Seedlings under Drought Stress. JKUAT. <http://hdl.handle.net/123456789/4427>.
- Bahadur, A., Chatterjee, A., Kumar, R., Singh, M., Naik, P., 2011. Physiological and biochemical basis of drought tolerance in vegetables. *Vegetable Sci* 38 (1), 1–16.
- Barnawal, D., Maji, D., Bharti, N., Chanotiya, C.S., Kalra, A., 2013. ACC Deaminase-Containing *Bacillus subtilis* Reduces stress ethylene-induced damage and improves mycorrhizal colonization and rhizobial nodulation in *Trigonella foenum-graecum* under drought stress. *J. Plant Growth Regul.* 32 (4), 809–822.
- Bashir, K., Matsui, A., Rasheed, S., Seki, M., 2019. Recent advances in the characterization of plant transcriptomes in response to drought, salinity, heat, and cold stress. *F1000Research* 8, 658.
- Behrooz, A., Vahdati, K., Rejali, F., Lotfi, M., Sarikhani, S., Leslie, C., 2019. Arbuscular mycorrhiza and plant growth-promoting bacteria alleviate drought stress in walnut. *Hortic. Sci. (Calcutta)* 54 (6), 1087–1092.
- Belimov, A., Dodd, I., Safronova, V., Shaposhnikov, A., Azarova, T., Makarova, N., Davies, W., Tikhonovich, I., 2015. Rhizobacteria that produce auxins and contain 1-amino-cyclopropane-1-carboxylic acid deaminase decrease amino acid concentrations in the rhizosphere and improve growth and yield of well-watered and water-limited potato (*Solanum tuberosum*). *Ann. Appl. Biol.* 167 (1), 11–25.
- Belimov, A.A., Zinovkina, N.Y., Safronova, V.I., Litvinsky, V.A., Nosikov, V.V., Zavalin, A.A., Tikhonovich, I.A., 2019. Rhizobial ACC deaminase contributes to efficient symbiosis with pea (*Pisum sativum* L.) under single and combined cadmium and water deficit stress. *Environ. Exp. Bot.* 167, 103859.
- Benabdellah, K., Abbas, Y., Abourouh, M., Aroca, R., Azcón, R., 2011. Influence of two bacterial isolates from degraded and non-degraded soils and arbuscular mycorrhizae fungi isolated from semi-arid zone on the growth of *Trifolium repens* under drought conditions: mechanisms related to bacterial effectiveness. *Eur. J. Soil Biol.* 47 (5), 303–309.
- Bhutan, K., 2006. National adaptation programme of action. In: Submitted to the United Nations Framework Convention on Climate Change.
- Bisognin, D.A., 2011. Breeding vegetatively propagated horticultural crops. *Crop Breed. Appl. Biotechnol.* 11 (SPE), 35–43.
- Bota, J., Medrano, H., Flexas, J., 2004. Is photosynthesis limited by decreased Rubisco activity and RuBP content under progressive water stress? *New Phytol.* 162 (3), 671–681.
- Buchanan, C.D., Lim, S., Salzman, R.A., Kagiampakis, I., Morishige, D.T., Weers, B.D., Klein, R.R., Pratt, L.H., Gondonner-Pratt, M.-M., Klein, P.E., 2005. *Sorghum bicolor*'s transcriptome response to dehydration, high salinity and ABA. *Plant Mol. Biol.* 58 (5), 699–720.
- Cherni, M., Ferjani, R., Mapelli, F., Boudabous, A., Borin, S., Ouzari, H.-I., 2019. Soil parameters drive the diversity of *Citrus sinensis* rhizosphere microbiota which exhibits a potential in plant drought stress alleviation. *Appl. Soil Ecol.* 135, 182–193.
- Chiappero, J., Cappellari, L.d.R., Sosa Alderete, L.G., Palermo, T.B., Banchio, E., 2019. Plant growth promoting rhizobacteria improve the antioxidant status in *Mentha piperita* grown under drought stress leading to an enhancement of plant growth and total phenolic content. *Ind. Crop. Prod.* 139, 111553.
- Dai, B., Yang, H., Dai, X., Wang, W., Wu, S., Zhao, X., Xiao, Y., 2019. Microbial composition changes on the surface of strawberries from the field and market by 16S rDNA sequencing. *J. Food Saf.* 39 (4), e12630.
- Datta, S., 2013. Impact of climate change in Indian horticulture—a review. *Int. J. Sci. Environ. Technol.* 2 (4), 661–671.
- Desclaux, D., Roumet, P., 1996. Impact of drought stress on the phenology of two soybean (*Glycine max* L. Merr.) cultivars. *Field Crop. Res.* 46 (1–3), 61–70.
- DhaifAllah, A.A.A., Hashim, N.B.M., Awang, A.B., 2018. Drought risk assessment using remote sensing and GIS in Yemen. *Int. J. Pure Appl. Math.* 118 (24).
- Eke, P., Kumar, A., Sahu, K.P., Wakam, L.N., Sheoran, N., Ashajothi, M., Patel, A., Fekam, F.B., 2019. Endophytic bacteria of desert cactus (*Euphorbia trigona* Mill.) confer drought tolerance and induce growth promotion in tomato (*Solanum lycopersicum* L.). *Microbiol. Res.* 228, 126302.
- El-Tarabily, K.A., 2008. Promotion of tomato (*Lycopersicon esculentum* Mill.) plant growth by rhizosphere competent 1-aminocyclopropane-1-carboxylic acid deaminase-producing streptomycete actinomycetes. *Plant Soil* 308 (1), 161–174.
- Erdogan, U., Çakmakçı, R., Varmazyari, A., Turan, M., Erdogan, Y., Ktir, N., 2016. Role of inoculation with multi-trait rhizobacteria on strawberries under water deficit stress. *Zemdirbyste-Agriculture* 103 (1), 67–76.

- Farooq, M., Basra, S., Wahid, A., Cheema, Z., Cheema, M., Khaliq, A., 2008. Physiological role of exogenously applied glycinebetaine to improve drought tolerance in fine grain aromatic rice (*Oryza sativa* L.). *J. Agron. Crop Sci.* 194 (5), 325–333.
- Farooq, M., Bramley, H., Palta, J.A., Siddique, K.H., 2011. Heat stress in wheat during reproductive and grain-filling phases. *Crit. Rev. Plant Sci.* 30 (6), 491–507.
- Farooq, M., Hussain, M., Wahid, A., Siddique, K., 2012. Drought stress in plants: an overview. In: *Plant Responses to Drought Stress*, pp. 1–33.
- Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., Basra, S.M.A., 2009. Plant drought stress: effects, mechanisms and management. In: Lichtfouse, E., Navarrete, M., Debaeke, P., Véronique, S., Alberola, C. (Eds.), *Sustainable Agriculture*. Springer Netherlands, Dordrecht, pp. 153–188.
- Fasusi, O.A., Cruz, C., Babalola, O.O., 2021. Agricultural sustainability: microbial biofertilizers in rhizosphere management. *Agriculture* 11 (2), 163.
- Fathi, A., Tari, D.B., 2016. Effect of drought stress and its mechanism in plants. *Int. J. Life Sci.* 10 (1), 1–6.
- Figueredo, M.V.B., Burity, H.A., Martínez, C.R., Chanway, C.P., 2008. Alleviation of drought stress in the common bean (*Phaseolus vulgaris* L.) by co-inoculation with *Paenibacillus polymyxa* and *Rhizobium tropici*. *Appl. Soil Ecol.* 40 (1), 182–188.
- Forchetti, G., Masciarelli, O., Izaguirre, M.J., Alemanno, S., Alvarez, D., Abdala, G., 2010. Endophytic bacteria improve seedling growth of sunflower under water stress, produce salicylic acid, and inhibit growth of pathogenic fungi. *Curr. Microbiol.* 61 (6), 485–493.
- Funk, C., 2011. We thought trouble was coming. *Nature News* 476 (7358), 7.
- Gahoonia, T.S., Raza, S., Nielsen, N.E., 1994. Phosphorus depletion in the rhizosphere as influenced by soil moisture. *Plant Soil* 159 (2), 213–218.
- Gamalerò, E., Marzachi, C., Galetto, L., Veratti, F., Massa, N., Bona, E., Novello, G., Glick, B.R., Ali, S., Cantamessa, S., 2017. An L-1-aminocyclopropane-1-carboxylate (ACC) deaminase-expressing endophyte increases plant resistance to flavescence dorée phytoplasma infection. *Plant Biosyst.* 151 (2), 331–340.
- Gholami, M., Rahemi, M., Kholdebarin, B., 2010. Effect of drought stress induced by polyethylene glycol on seed germination of four wild almond species. *Aust. J. Appl. Sci.* 4 (5), 785–791.
- Glick, B.R., Todorovic, B., Czarny, J., Cheng, Z., Duan, J., McConkey, B., 2007. Promotion of plant growth by bacterial ACC deaminase. *Crit. Rev. Plant Sci.* 26 (5–6), 227–242.
- Goicoechea, N., Antolin, M., Sánchez-Díaz, M., 1997. Influence of arbuscular mycorrhizae and *Rhizobium* on nutrient content and water relations in drought stressed alfalfa. *Plant Soil* 192 (2), 261–268.
- Guerrieri, M.C., Fanfoni, E., Fiorini, A., Trevisan, M., Puglisi, E., 2020. Isolation and screening of extracellular PGPR from the rhizosphere of tomato plants after long-term reduced tillage and cover crops. *Plants* 9 (5), 668.
- Gupta, S., Pandey, S., 2019. Unravelling the biochemistry and genetics of ACC deaminase—An enzyme alleviating the biotic and abiotic stress in plants. *Plant Gene* 18, 100175.
- Habibi, G., 2018. Effects of mild and severe drought stress on the biomass, phenolic compounds production and photochemical activity of *Aloe vera* (L.) Burm. f. *Acta Agric. Slov.* 111 (2), 463–476.
- Hamal, K., Sharma, S., Khadka, N., Haile, G.G., Joshi, B.B., Xu, T., Dawadi, B., 2020. Assessment of drought impacts on crop yields across Nepal during 1987–2017. *Meteorol. Appl.* 27 (5), e1950.
- Hanci, F., Cebeçi, E., 2014. Investigation of proline, chlorophyll and carotenoids changes under drought stress in some onion (*Allium cepa* L.) cultivars. *Türk Tarım ve Doğa Bilimleri Dergisi* 1 (Özel Sayı-2), 1499–1504.
- Hariprasad, P., Venkateswaran, G., Niranjana, S., 2014. Diversity of cultivable rhizobacteria across tomato growing regions of Karnataka. *Biol. Control* 72, 9–16.
- Harris, D., Tripathi, R., Joshi, A., 2002. On-farm seed priming to improve crop establishment and yield in dry direct-seeded rice. In: *Direct Seeding: Research Strategies and Opportunities*. International Research Institute, Manila, Philippines, pp. 231–240.
- Hazarika, T., 2013. Climate change and Indian horticulture: opportunities, challenges and mitigation strategies. *Int. J. Environ. Eng. Manag.* 4 (6), 629–630.
- Hennessy, K., Fawcett, R., Kirono, D., Mpelasoka, F., Jones, D., Bathols, J., Whetton, P., Stafford Smith, M., Howden, M., Mitchell, C., 2008. An Assessment of the Impact of Climate Change on the Nature and Frequency of Exceptional Climatic Events.
- Hossain, M., 1990. Natural calamities, instability in production and food policy in Bangladesh. *Bangladesh Dev. Stud.* 33–54.
- Hou, X., Wu, F., Wang, X.J., Sun, Z.T., Zhang, Y., Yang, M.T., Bai, H., Li, S., Bai, J.G., 2018. *Bacillus methylotrophicus* CSY-F1 alleviates drought stress in cucumber (*Cucumis sativus*) grown in soil with high ferulic acid levels. *Plant Soil* 431 (1), 89–105.
- Hounam, C., CE, H., JJ, B., MS, K., WC, P., 1975. Drought and Agriculture.
- Hu, Y., Schmidhalter, U., 2005. Drought and salinity: a comparison of their effects on mineral nutrition of plants. *J. Plant Nutr.* 28 (4), 541–549.
- Huang, B., DaCosta, M., Jiang, Y., 2014. Research advances in mechanisms of turfgrass tolerance to abiotic stresses: from physiology to molecular biology. *Crit. Rev. Plant Sci.* 33 (2–3), 141–189.
- Inthama, P., Pumas, P., Pathom-Aree, W., Pekkoh, J., Pumas, C., 2021. Plant Growth and Drought tolerance-promoting bacterium for bioremediation of paraquat pesticide residues in agriculture soils. *Front. Microbiol.* 12, 446.
- Jahanbazy Goujani, H., Hosseini Nasr, S.M., Sagheb-Talebi, K., Hojjati, S.M., 2013. Effect of drought stress induced by altitude, on four wild almond species. *Iranian J. For. Poplar Res.* 21 (2), 373–386.
- Jha, S., Jaiswal, P., Narsaiah, K., Bhardwaj, R., Kaur, P.P., Singh, A.K., Sharma, R., Kumar, R., 2012. Postharvest microbial diversity on major cultivars of Indian mangoes. *J. Appl. Hort.* 14 (2), 102–109.
- Jie, Z., Yuncong, Y., Yuping, Z., 2008. Effects of drought stress on the photosynthesis of wild apricot. *Acta Hort.* (772), 287.
- Kage, H., Kochler, M., Stützel, H., 2004. Root growth and dry matter partitioning of cauliflower under drought stress conditions: measurement and simulation. *Eur. J. Agron.* 20 (4), 379–394.
- Kannan, N., Kul, G., 2011. Drought induced changes in physiological, biochemical and phytochemical properties of *Withania somnifera* Dun. *J. Med. Plants Res.* 5 (16), 3929–3935.
- Kasim, W.A., Osman, M.E., Omar, M.N., Abd El-Daim, I.A., Bejai, S., Meijer, J., 2013. Control of drought stress in wheat using plant-growth-promoting bacteria. *J. Plant Growth Regul.* 32 (1), 122–130.
- Kaur, T., Devi, R., Kour, D., Yadav, A., Yadav, A.N., 2021a. Plant growth promotion of barley (*Hordeum vulgare* L.) by potassium solubilizing bacteria with multifarious plant growth promoting attributes. *Plant Sci. Today* 8, 17–24.
- Kaur, T., Devi, R., Kour, D., Yadav, A., Yadav, A.N., Dikilitas, M., et al., 2021b. Plant growth promoting soil microbiomes and their potential implications for agricultural and environmental sustainability. *Biologia* 76, 2687–2709.
- Kaushal, M., Wani, S.P., 2016. Plant-growth-promoting rhizobacteria: drought stress alleviators to ameliorate crop production in drylands. *Ann. Microbiol.* 66 (1), 35–42.
- Kawalekar, J.S., 2013. Role of biofertilizers and biopesticides for sustainable agriculture. *J. Bio. Innovat.* 2 (3), 73–78.
- Kaya, M.D., Okçu, G., Atak, M., Cıkkılı, Y., Kolsarıcı, Ö., 2006. Seed treatments to overcome salt and drought stress during germination in sunflower (*Helianthus annuus* L.). *Eur. J. Agron.* 24 (4), 291–295.
- Khan, N., Bano, A., Rahman, M.A., Guo, J., Kang, Z., Babar, M.A., 2019. Comparative physiological and metabolic analysis reveals a complex mechanism involved in drought tolerance in chickpea (*Cicer arietinum* L.) induced by PGPR and PGRs. *Sci. Rep.* 9 (1), 2097.
- Kiani, S.P., Talia, P., Maury, P., Grieu, P., Heinz, R., Perrault, A., Nishinakamu, V., Hopp, E., Gentzbittel, L., Paniego, N., Sarrafi, A., 2007. Genetic analysis of plant water status and osmotic adjustment in recombinant inbred lines of sunflower under two water treatments. *Plant Sci.* 172 (4), 773–787.
- Kim, Y.-N., Khan, M.A., Kang, S.-M., Hamayun, M., Lee, I.-J., 2020. Enhancement of drought-stress tolerance of *Brassica oleracea* var. italica L. by newly isolated *Variovorax* sp. YNA59. *J. Microbiol. Biotechnol.* 30, 1500–1509.
- Kour, D., Rana, K.L., Kaur, T., Devi, R., Yadav, N., Halder, S.K., et al., 2020. Potassium solubilizing and mobilizing microbes: biodiversity, mechanisms of solubilization and biotechnological implication for alleviations of abiotic stress. In: Rastegari, A.A., Yadav, A.N., Yadav, N. (Eds.), *Trends of Microbial Biotechnology for Sustainable Agriculture and Biomedicine Systems: Diversity and Functional Perspective*. Elsevier, Amsterdam, pp. 177–202.
- Kour, D., Rana, K.L., Kaur, T., Sheikh, I., Yadav, A.N., Kumar, V., Dhaliwal, H.S., Saxena, A.K., 2020a. Microbe-mediated alleviation of drought stress and acquisition of phosphorus in great millet (*Sorghum bicolor* L.) by drought-adaptive and phosphorus-solubilizing microbes. *Biocatal. Agric. Biotechnol.* 23, 101501.
- Kour, D., Rana, K.L., Kaur, T., Yadav, N., Yadav, A.N., Kumar, M., et al., 2021. Biodiversity, current developments and potential biotechnological applications of phosphorus-solubilizing and-mobilizing microbes: a review. *Pedosphere* 31 (1), 43–75.
- Kour, D., Rana, K.L., Sheikh, I., Kumar, V., Yadav, A.N., Dhaliwal, H.S., Saxena, A.K., 2020b. Alleviation of drought stress and plant growth promotion by *Pseudomonas libanensis* EU-LWNA-33, a drought-adaptive phosphorus-solubilizing bacterium. *Proc. Natl. Acad. Sci. India B Biol. Sci.* 90, 785–795.
- Kour, D., Rana, K.L., Yadav, A.N., Sheikh, I., Kumar, V., Dhaliwal, H.S., Saxena, A.K., 2020c. Amelioration of drought stress in Foxtail millet (*Setaria italica* L.) by P-solubilizing drought-tolerant microbes with multifarious plant growth promoting attributes. *Environ. Sustain.* 3, 23–34.
- Kour, D., Rana, K.L., Yadav, A.N., Yadav, N., Kumar, V., Kumar, A., Sayyed, R., Hesham, A.E.L., Dhaliwal, H.S., Saxena, A.K., 2019. Drought-tolerant Phosphorus-Solubilizing Microbes: Biodiversity and Biotechnological Applications for Alleviation of Drought Stress in Plants, Plant Growth Promoting Rhizobacteria for Sustainable Stress Management. Springer, pp. 255–308.
- Kour, D., Yadav, A.N., 2020. Microbe mediated mitigation of drought stress in crops. *Agric. Lett.* 1, 79–82.
- Kuchenbuch, R., Claassen, N., Jungk, A., 1986. Potassium availability in relation to soil moisture. *Plant Soil* 95, 233–243.
- La Fua, J., Sabaruddin, L., Leomo, S., GA, K.S., Khaeruni, A., Safuan, O., Hs, G., Iswandi, M., Nurlila, U., 2021. Isolation of drought-tolerant endophyte bacteria from local tomato plants. *Pakistan J. Biol. Sci.: PJB* 24, 1055–1062.
- Lambers, H., Chapin III, F.S., Pons, T.L., 2008. *Plant Physiological Ecology*. Springer Science & Business Media.
- Levander, O.A., 1990. Fruit and vegetable contributions to dietary mineral intake in human health and disease. *Hortic. Sci. (Calcutta)* 25 (12), 1486–1488.
- Liang, C., Wang, W., Wang, J., Ma, J., Li, C., Zhou, F., Zhang, S., Yu, Y., Zhang, L., Li, W., 2017. Identification of differentially expressed genes in sunflower (*Helianthus annuus*) leaves and roots under drought stress by RNA sequencing. *Botanical Stud.* 58 (1), 1–11.
- Liang, G., Liu, J., Zhang, J., Guo, J., 2020. Effects of drought stress on photosynthetic and physiological parameters of tomato. *J. Am. Soc. Hortic. Sci.* 145 (1), 12–17.
- Liao, X., Chen, J., Guan, R., Liu, J., Sun, Q., 2021. Two arbuscular mycorrhizal fungi alleviates drought stress and improves plant growth in *Cinnamomum migao* seedlings. *MYCOBIOLOGY* 49 (4), 396–405.
- Lim, J.-H., Kim, S.-D., 2013. Induction of drought stress resistance by multi-functional PGPR *Bacillus licheniformis* K11 in pepper. *Plant Pathol. J.* 29 (2), 201.
- Liu, F., Jensen, C.R., Andersen, M.N., 2004. Drought stress effect on carbohydrate concentration in soybean leaves and pods during early reproductive development: its implication in altering pod set. *Field Crop. Res.* 86 (1), 1–13.
- Liu, X., Zhang, J., Ma, D., Bao, Y., Tong, Z., Liu, X., 2013. Dynamic risk assessment of drought disaster for maize based on integrating multi-sources data in the region of the northwest of Liaoning Province, China. *Nat. Hazards* 65 (3), 1393–1409.

- Lotfi, N., Soleimani, A., Vahdati, K., Çakmakçı, R., 2019. Comprehensive biochemical insights into the seed germination of walnut under drought stress. *Sci. Hortic.* 250, 329–343.
- Lotfi, N., Vahdati, K., Hassani, D., Kholdebarin, B., Amiri, R., 2009. Peroxidase, guaiacol peroxidase and ascorbate peroxidase activity accumulation in leaves and roots of walnut trees in response to drought stress. *VI Int. Walnut Sympos.* 861, 309–316.
- Mahdi, S.S., Hassan, G., Samoon, S., Rather, H., Dar, S.A., Zehra, B., 2010. Bio-fertilizers in organic agriculture. *J. Phyto.* 2, 42–54.
- Mahmood Aulakh, A., Qadir, G., Hassan, F.U., Hayat, R., Sultan, T., Billah, M., Hussain, M., Khan, N., 2020. Desert soil microbes as a mineral nutrient acquisition tool for chickpea (*Cicer arietinum* L.) productivity at different moisture regimes. *Plants* 9 (12), 1629.
- Marasco, R., Rolli, E., Ettoumi, B., Vigani, G., Mapelli, F., Borin, S., Abou-Hadid, A.F., El-Behairy, U.A., Sorlini, C., Cherif, A., 2012. A drought resistance-promoting microbiome is selected by root system under desert farming. *PLoS One* 7 (10), e48479.
- Maxton, A., Singh, P., Masih, S.A., 2018. ACC deaminase-producing bacteria mediated drought and salt tolerance in *Capsicum annum*. *J. Plant Nutr.* 41 (5), 574–583.
- Mayak, S., Tirosch, T., Glick, B.R., 2004. Plant growth-promoting bacteria that confer resistance to water stress in tomatoes and peppers. *Plant Sci.* 166 (2), 525–530.
- McGarvey, J., Han, R., Connell, J., Stanker, L., Hnasko, R., 2015. Bacterial populations on the surfaces of organic and conventionally grown almond drupes. *J. Appl. Microbiol.* 119 (2), 529–538.
- Mehta, P., Walia, A., Shirkot, C., 2015. Functional diversity of phosphate solubilizing plant growth promoting rhizobacteria isolated from apple trees in the trans Himalayan region of Himachal Pradesh, India. *Biol. Agric. Hortic.* (BAH) 31, 265–288.
- Miller, G., Suzuki, N., Giftci-Yilmaz, S., Mittler, R., 2010. Reactive oxygen species homeostasis and signalling during drought and salinity stresses. *Plant Cell Environ.* 33 (4), 453–467.
- Mirzabaev, A., Wu, J., Evans, J., Garcia-Oliva, F., Hussein, I., Iqbal, M., Kimutai, J., Knowles, T., Meza, F., Nedjraoui, D., 2019. Desertification, Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. [Hentet fra. https://www.ipcc.ch/srccl](https://www.ipcc.ch/srccl).
- Mishra, V., Tiwari, A.D., Aadhar, S., Shah, R., Xiao, M., Pai, D., Lettenmaier, D., 2019. Drought and famine in India, 1870–2016. *Geophys. Res. Lett.* 46 (4), 2075–2083.
- Miyani, M.A., 2015. Droughts in Asian least developed countries: vulnerability and sustainability. *Weather Clim. Extrem.* 7, 8–23.
- Moussa, T.A., 2002. Studies on biological control of sugarbeet pathogen *Rhizoctonia solani* Kühn. *J. Biol. Sci.* 2 (12), 800–804.
- Muhammad, A., Kumar Jha, S., Rasmussen, P.F., 2017. Drought characterization for a snow-dominated region of Afghanistan. *J. Hydrol. Eng.* 22 (8), 05017014.
- Murshid, K., 1987. Weather, new technology and instability in foodgrain production in Bangladesh. *Bangladesh Dev. Stud.* 31–56.
- Naveed, M., Mitter, B., Reichenauer, T.G., Wiecezorek, K., Sessitsch, A., 2014. Increased drought stress resilience of maize through endophytic colonization by *Burkholderia phytofirmans* PsJN and *Enterobacter* sp. FD17. *Environ. Exp. Bot.* 97, 30–39.
- Nazir, U., Zargar, M., Baba, Z., Mir, S., Mohiddin, F., Bhat, N., 2020. Isolation and characterization of plant growth promoting rhizobacteria associated with pea rhizosphere in North Himalayan region. *Int. J. Chem. Stud.* 8, 1131–1135.
- Ngumbi, E., Klopper, J., 2016. Bacterial-mediated drought tolerance: current and future prospects. *Appl. Soil Ecol.* 105, 109–125.
- Nonami, H., 1998. Plant water relations and control of cell elongation at low water potentials. *J. Plant Res.* 111 (3), 373–382.
- Osman, N.I., Yin, S., 2018. Isolation and characterization of pea plant (*Pisum sativum* L.) growth-promoting Rhizobacteria. *Afr. J. Microbiol. Res.* 12 (34), 820–828.
- Passos, J.F.M.d., Costa, P.B.d., Costa, M.D., Zaffari, G.R., Nava, G., Boneti, J.L., Oliveira, A.M.R.d., Passaglia, L.M., 2014. Cultivable bacteria isolated from apple trees cultivated under different crop systems: diversity and antagonistic activity against *Colletotrichum gloeosporioides*. *Genet. Mol. Biol.* 37 (3), 560–572.
- Pervez, M., Ayub, C., Khan, H., Shahid, M., Ashraf, I., 2009. Effect of drought stress on growth, yield and seed quality of tomato (*Lycopersicon esculentum* L.). *Pakistan J. Agric. Sci.* 46 (3), 174–178.
- Portal, P.W., 2011. History of Drought in Pakistan—in Detail.
- Prívarová, A., Prívarová, M., 2019. Nexus between climate change, displacement and conflict: Afghanistan case. *Sustainability* 11 (20), 5586.
- Püschel, D., Bitterlich, M., Rydlová, J., Jansa, J., 2021. Drought accentuates the role of mycorrhiza in phosphorus uptake. *Soil Biol. Biochem.* 157, 108243.
- Pathiyottil, P., Akkara, Y., 2021. Pre treatment with *Bacillus subtilis* mitigates drought induced photo-oxidative damages in okra by modulating antioxidant system and photochemical activity. *Physiol. Mol. Biol. Plants* 27 (5), 945–957.
- Raghothama, K., Karthikeyan, A., 2005. Phosphate acquisition. *Plant Soil* 274 (1), 37–49.
- Rahman, M., 1995. Responding to drought in Bangladesh. *The Daily Star* 15 (8).
- Rana, K.L., Kour, D., Kaur, T., Devi, R., Yadav, A.N., Yadav, N., et al., 2020. Endophytic microbes: biodiversity, plant growth-promoting mechanisms and potential applications for agricultural sustainability. *Antonie Leeuwenhoek* 113, 1075–1107.
- Ravanbakhsh, M., Sasidharan, R., Voesenek, L.A.C.J., Kowalchuk, G.A., Jousset, A., 2018. Microbial modulation of plant ethylene signaling: ecological and evolutionary consequences. *Microbiome* 6 (1), 52.
- Reddy, A.R., Chaitanya, K.V., Vivekanandan, M., 2004. Drought-induced responses of photosynthesis and antioxidant metabolism in higher plants. *J. Plant Physiol.* 161 (11), 1189–1202.
- Reina-Bueno, M., Argandoña, M., Nieto, J.J., Hidalgo-García, A., Iglesias-Guerra, F., Delgado, M.J., Vargas, C., 2012. Role of trehalose in heat and desiccation tolerance in the soil bacterium *Rhizobium etli*. *BMC Microbiol* 12 (1), 1–17.
- Roberts, M.S., Nakamura, L., Cohan, F.M., 1994. *Bacillus mojavensis* sp. nov., distinguishable from *Bacillus subtilis* by sexual isolation, divergence in DNA sequence, and differences in fatty acid composition. *Int. J. Syst. Evol. Microbiol.* 44 (2), 256–264.
- Rouphael, Y., Cardarelli, M., Schwarz, D., Franken, P., Colla, G., 2012. Effects of Drought on Nutrient Uptake and Assimilation in Vegetable Crops, *Plant Responses to Drought Stress*. Springer, pp. 171–195.
- Ruiz-Lozano, J., Aczón, R., 1996. Mycorrhizal colonization and drought stress as factors affecting nitrate reductase activity in lettuce plants. *Agric. Ecosyst. Environ.* 60 (2–3), 175–181.
- Saikia, J., Sarma, R.K., Dhandia, R., Yadav, A., Bharali, R., Gupta, V.K., Saikia, R., 2018. Alleviation of drought stress in pulse crops with ACC deaminase producing rhizobacteria isolated from acidic soil of Northeast India. *Sci. Rep.* 8 (1), 1–16.
- Saleem, A.R., Brunetti, C., Khalid, A., Della Rocca, G., Raio, A., Emiliani, G., De Carlo, A., Mahmood, T., Centritto, M., 2018. Drought response of *Mucuna pruriens* (L.) DC. inoculated with ACC deaminase and IAA producing rhizobacteria. *PLoS One* 13 (2), e0191218.
- Salehi-Lisar, S.Y., Bakhshayeshan-Agdam, H., 2016. Drought stress in plants: causes, consequences, and tolerance. In: *Drought Stress Tolerance in Plants*, I. Springer, pp. 1–16.
- Sarma, R.K., Saikia, R., 2014. Alleviation of drought stress in mung bean by strain *Pseudomonas aeruginosa* GGRJ21. *Plant Soil* 377 (1), 111–126.
- Schachtman, D.P., Reid, R.J., Ayling, S.M., 1998. Phosphorus uptake by plants: from soil to cell. *Plant Physiol.* 116 (2), 447–453.
- Schlauch, K.A., Grimplet, J., Cushman, J., Cramer, G.R., 2010. Transcriptomics Analysis Methods: Microarray Data Processing, Analysis and Visualization Using the Affymetrix Genechip® Vitis Vinifera Genome Array, *Methodologies and Results in grapevine Research*. Springer, pp. 317–334.
- Schwarz, D., Heinen, M., Van Noordwijk, M., 1995. Rooting characteristics of lettuce grown in irrigated sand beds. *Plant Soil* 176 (2), 205–217.
- Seki, M., Kamei, A., Yamaguchi-Shinozaki, K., Shinozaki, K., 2003. Molecular responses to drought, salinity and frost: common and different paths for plant protection. *Curr. Opin. Biotechnol.* 14 (2), 194–199.
- Seki, M., Umezawa, T., Urano, K., Shinozaki, K., 2007. Regulatory metabolic networks in drought stress responses. *Curr. Opin. Plant Biol.* 10 (3), 296–302.
- Selvakumar, G., Bhatt, R.M., Upreti, K.K., Bindu, G.H., Shweta, K., 2015. *Citricoccus zhacaiensis* B-4 (MTCC 12119) a novel osmotolerant plant growth promoting actinobacterium enhances onion (*Allium cepa* L.) seed germination under osmotic stress conditions. *World J. Microbiol. Biotechnol.* 31 (5), 833–839.
- Serraj, R., Sinclair, T., 2002. Osmolyte accumulation: can it really help increase crop yield under drought conditions? *Plant Cell Environ.* 25 (2), 333–341.
- Sharp, R.G., Chen, L., Davies, W.J., 2011. Inoculation of growing media with the rhizobacterium *Variovorax paradoxus* 5C-2 reduces unwanted stress responses in hardy ornamental species. *Sci. Hortic.* 129 (4), 804–811.
- Sheffield, J., Wood, E.F., Roderick, M.L., 2012. Little change in global drought over the past 60 years. *Nature* 491 (7424), 435–438.
- Sheibani-Tezerji, R., Rattei, T., Sessitsch, A., Trognitz, F., Mitter, B., 2015. Transcriptome profiling of the endophyte *Burkholderia phytofirmans* PsJN indicates sensing of the plant environment and drought stress. *mBio* 6 (5), e00621–615.
- Sherpa, M.T., Bag, N., Das, S., Haokip, P., Sharma, L., 2021. Isolation and characterization of plant growth promoting rhizobacteria isolated from organically grown high yielding pole type native pea (*Pisum sativum* L.) variety Dentami of Sikkim, India. *Curr. Res. Microb. Sci.* 2, 100068.
- Shin, Y.K., Bhandari, S.R., Jo, J.S., Song, J.W., Lee, J.G., 2021. Effect of drought stress on chlorophyll fluorescence parameters, phytochemical contents, and antioxidant activities in lettuce seedlings. *Horticulturae* 7 (8), 238.
- Shirinbayan, S., Khosravi, H., Malakouti, M.J., 2019. Alleviation of drought stress in maize (*Zea mays*) by inoculation with *Azotobacter* strains isolated from semi-arid regions. *Appl. Soil Ecol.* 133, 138–145.
- Silveira, J.A.G.d., Costa, R.C.L.d., Oliveira, J.T.A., 2001. Drought-induced effects and recovery of nitrate assimilation and nodule activity in cowpea plants inoculated with *Bradyrhizobium* spp. under moderate nitrate level. *Braz. J. Microbiol.* 32, 187–194.
- Smika, D.E., Haas, H., Power, J., 1965. Effects of moisture and nitrogen fertilizer on growth and water use by native grass 1. *Agron. J.* 57 (5), 483–486.
- Snook, M.E., Mitchell, T., Hinton, D.M., Bacon, C.W., 2009. Isolation and characterization of Leu7-surfactin from the endophytic bacterium *Bacillus mojavensis* RRC 101, a biocontrol agent for *Fusarium verticillioides*. *J. Agric. Food Chem.* 57 (10), 4287–4292.
- Snyder, R.L., 2017. Climate change impacts on water use in horticulture. *Horticulturae* 3 (2), 27.
- Sonah, H., Deshmukh, R.K., Singh, V.P., Gupta, D.K., Singh, N.K., Sharma, T.R., 2011. Genomic resources in horticultural crops: status, utility and challenges. *Biotechnol. Adv.* 29 (2), 199–209.
- Soni, R., Kapoor, R., Kaur, M., 2016. Evaluation of siderophore production and antimicrobial activity by fluorescent pseudomonas diversity associated with rhizosphere of apple and pear. *Int. J. Agric. Environ. Biotechnol.* 9 (6), 1109–1115.
- Sorensen, J., Grevsen, K., 2001. Sprouting in bulb onions (*Allium cepa* L.) as influenced by nitrogen and water stress. *J. Hortic. Sci. Biotechnol.* 76 (4), 501–506.
- Sporleder, M., Lacey, L.A., 2013. Biopesticides.
- Subramanian, K., Santhanakrishnan, P., Balasubramanian, P., 2006. Responses of field grown tomato plants to arbuscular mycorrhizal fungal colonization under varying intensities of drought stress. *Sci. Hortic.* 107 (3), 245–253.
- Sudarma, I.M., Suprpta, D.N., 2011. Diversity of soil microorganisms in banana habitat with and without Fusarium wilt symptom. *J. Int. Soc. Southeast Asian Agric. Sci.* 17 (1), 147–159.
- Sukweenadhi, J., Kim, Y.J., Choi, E.S., Koh, S.C., Lee, S.W., Kim, Y.J., Yang, D.C., 2015. *Paenibacillus yonginensis* DCY84T induces changes in *Arabidopsis thaliana* gene expression against aluminum, drought, and salt stress. *Microbiol. Res.* 172, 7–15.

- Tahir, F., Ibrahim, M., Hamid, K., 2003. Effect of drought stress on vegetative and reproductive growth behaviour of mango (*Mangifera indica* L.). *Asian J. Plant Sci.* 2, 116–118.
- Tallapragada, P., Dikshit, R., Seshagiri, S., 2016. Influence of *Rhizophagus* spp. and *Burkholderia seminalis* on the growth of tomato (*Lycopersicon esculatum*) and bell pepper (*Capsicum annuum*) under drought stress. *Commun. Soil Sci. Plant Anal.* 47 (17), 1975–1984.
- Tan, Y., hui Zhu, T., jiang Li, S., 2020. Structural and dynamic analysis of phyllosphere fungal community of walnut leaves infected by leaf spot disease based illumina high-throughput sequencing technology. *Authorea Preprints*.
- Tardieu, F., Parent, B., Caldeira, C.F., Welcker, C., 2014. Genetic and physiological controls of growth under water deficit. *Plant Physiol.* 164 (4), 1628–1635.
- Thakur, N., Kaur, S., Tomar, P., Thakur, S., Yadav, A.N., 2020. Microbial biopesticides: current status and advancement for sustainable agriculture and environment. In: Rastegari, A.A., Yadav, A.N., Yadav, N. (Eds.), *Trends of Microbial Biotechnology for Sustainable Agriculture and Biomedicine Systems: Diversity and Functional Perspectives*. Elsevier, Amsterdam, pp. 243–282.
- Tiwari, P., Bajpai, M., Singh, L.K., Mishra, S., Yadav, A.N., 2020. Phytohormones producing fungal communities: metabolic engineering for abiotic stress tolerance in crops. In: Yadav, A.N., Mishra, S., Kour, D., Yadav, N., Kumar, A. (Eds.), *Agriculturally Important Fungi for Sustainable Agriculture, Volume 1: Perspective for Diversity and Crop Productivity*. Springer, Cham, pp. 1–25.
- Tsuchida, Y., Negoro, K., Hishiike, M., 2011. Effect of initiation timing of drought stress on carbohydrate content and vegetative growth in Japanese apricot (*Prunus mume* Sieb. et Zucc.) Nanko. *J. Japanese Soc. Hort. Sci.* 80 (1), 19–25.
- Ullah, U., Ashraf, M., Shahzad, S.M., Siddiqui, A.R., Piracha, M.A., Suleman, M., 2016. Growth behavior of tomato (*Solanum lycopersicum* L.) under drought stress in the presence of silicon and plant growth promoting rhizobacteria. *Soil Environ.* 35, 65–75.
- Vaishnav, A., Choudhary, D.K., 2019. Regulation of drought-responsive gene expression in *Glycine max* L. Merrill is mediated through *Pseudomonas simiae* strain AU. *J. Plant Growth Regul.* 38 (1), 333–342.
- Vega, F.E., Kaya, H.K., 2012. *Insect Pathology*. Academic Press.
- Verma, P., Yadav, A.N., Kumar, V., Singh, D.P., Saxena, A.K., 2017. Beneficial plant-microbes interactions: biodiversity of microbes from diverse extreme environments and its impact for crop improvement. In: Singh, D.P., Singh, H.B., Prabha, R. (Eds.), *Plant-Microbe Interactions in Agro-Ecological Perspectives: Volume 2: Microbial Interactions and Agro-Ecological Impacts*. Springer Singapore, Singapore, pp. 543–580.
- Vílchez, J.I., García-Fontana, C., Román-Naranjo, D., González-López, J., Manzanera, M., 2016. Plant drought tolerance enhancement by trehalose production of desiccation-tolerant microorganisms. *Front. Microbiol.* 7, 1577.
- Vitousek, P.M., Naylor, R., Crews, T., David, M.B., Drinkwater, L., Holland, E., Johns, P., Katzenberger, J., Martinelli, L., Matson, P., 2009. Nutrient imbalances in agricultural development. *Science* 324 (5934), 1519–1520.
- Vurukonda, S.S.K.P., Vardharajula, S., Shrivastava, M., SkZ, A., 2016. Enhancement of drought stress tolerance in crops by plant growth promoting rhizobacteria. *Microbiol. Res.* 184, 13–24.
- Wahid, A., Rasul, E., Rao, R., Iqbal, R., 2005. Photosynthesis in leaf, stem, flower and fruit. *Handbook of Photosynthesis* 2, 479–497.
- Wang, S.-Y., Yoon, J.-H., Gillies, R.R., Cho, C., 2013. What caused the winter drought in western Nepal during recent years? *J. Clim.* 26 (21), 8241–8256.
- Wong, G., Lambert, M., Leonard, M., Metcalfe, A., 2010. Drought analysis using trivariate copulas conditional on climatic states. *J. Hydrol. Eng.* 15 (2), 129–141.
- Wu, Q.-S., Xia, R.-X., Zou, Y.-N., 2008. Improved soil structure and citrus growth after inoculation with three arbuscular mycorrhizal fungi under drought stress. *Eur. J. Soil Biol.* 44 (1), 122–128.
- Xie, Z., Chu, Y., Zhang, W., Lang, D., Zhang, X., 2019. *Bacillus pumilus* alleviates drought stress and increases metabolite accumulation in *Glycyrrhiza uralensis* Fisch. *Environ. Exp. Bot.* 158, 99–106.
- Xu, J., Li, X.-L., Luo, L., 2012. Effects of engineered *Sinorhizobium meliloti* on cytokinin synthesis and tolerance of alfalfa to extreme drought stress. *Appl. Environ. Microbiol.* 78 (22), 8056–8061.
- Xu, M., Sheng, J., Chen, L., Men, Y., Gan, L., Guo, S., Shen, L., 2014. Bacterial community compositions of tomato (*Lycopersicon esculentum* Mill.) seeds and plant growth promoting activity of ACC deaminase producing *Bacillus subtilis* (HYT-12-1) on tomato seedlings. *World J. Microbiol. Biotechnol.* 30 (3), 835–845.
- Yadav, A.N., 2022. Phosphate-solubilizing microorganisms for agricultural sustainability. *J. Appl. Biol. Biotechnol.* 10, 1–6.
- Yadav, A.N., Rastegari, A.A., Yadav, N., Kour, D., 2020. *Advances in Plant Microbiome and Sustainable Agriculture: Diversity and Biotechnological Applications*. Springer, Singapore.
- Yasar, F., Uzal, O., Ozpay, T., 2010. Changes of the lipid peroxidation and chlorophyll amount of green bean genotypes under drought stress. *Afr. J. Agric. Res.* 5 (19), 2705–2709.
- Yin, B., Wang, Y., Liu, P., Hu, J., Zhen, W., 2010. Effects of vesicular-arbuscular mycorrhiza on the protective system in strawberry leaves under drought stress. *Front. Agric. China* 4 (2), 165–169.
- Youqiang, C., Jinmao, Z., Bingying, Y., 2000. Effects of drought stress on active oxygen damage and membrane lipid peroxidation of leaves in mango (*Mangifera indica* L.). *Sheng Ming Ke Xue Yan Jiu* 4 (1), 60–64.
- Youssef, M., Eissa, M., 2014. Biofertilizers and their role in management of plant parasitic nematodes. A review. *J. Biotechnol. Pharm. Res.* 5 (1), 1–6.
- Zaher-Ara, T., Boroomand, N., Sadat-Hosseini, M., 2016. Physiological and morphological response to drought stress in seedlings of ten citrus. *Trees (Berl.)* 30 (3), 985–993.
- Zardak, S.G., Dehnavi, M.M., Salehi, A., Gholamhoseini, M., 2018. Effects of using arbuscular mycorrhizal fungi to alleviate drought stress on the physiological traits and essential oil yield of fennel. *Rhizosphere* 6, 31–38.
- Zhang, L., Wang, S., 2017. Bacterial community diversity on in-shell walnut surfaces from six representative provinces in China. *Sci. Rep.* 7 (1), 1–9.
- Zhang, M., Yang, L., Hao, R., Bai, X., Wang, Y., Yu, X., 2020. Drought-tolerant plant growth-promoting rhizobacteria isolated from jujube (*Ziziphus jujuba*) and their potential to enhance drought tolerance. *Plant Soil* 452 (1), 423–440.
- Zhou, R., Yu, X., Ottosen, C.-O., Rosenqvist, E., Zhao, L., Wang, Y., Yu, W., Zhao, T., Wu, Z., 2017. Drought stress had a predominant effect over heat stress on three tomato cultivars subjected to combined stress. *BMC Plant Biol.* 17 (1), 1–13.
- Zokae-Khosroshahi, M., Esna-Ashari, M., Ershadi, A., Imani, A., 2014. Morphological changes in response to drought stress in cultivated and wild almond species. *Int. J. Hort. Sci. Technol.* 1 (1), 79–92.