Chapter 19
Medicinal Plants and Their Pharmaceutical Properties Under Adverse Environmental Conditions

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Contents

1 Introduction

Health is wealth. In consonance with this proverb, human beings have always been in search of various types of medicine to eliminate their illnesses. Plants are the natural source of these medicines mainly due to the presence of secondary metabolites and have been used as medicine in crude extract form. They have been also used to isolate the bioactive compounds in modern medicine and herbal medicine systems (Parveen et al. 2020a). Thus, they play an important role in the development, synthesis, and formulation of new drugs. Right now, numerous plant-based drugs are available in the market, and they have shown a remarkable contribution in disease management. In fact, from the ancient times, several herbal plants have been used as medicine or a source of medicines. For instance, in 2600 BC, the medicinal system in Mesopotamia had thousands of plant-derived medicines. Also, the

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Egyptian medicine system "Ebers Papyrus" has the written records of 700 drugs obtained from plants (Borchardt 2002; Cragg and Newman 2013; Sneader 2005). Traditional Chinese medicine and Indian Ayurveda and Unani medicine systems also documented evidence for the use of plant-derived medicine over thousands of years (Parveen et al. 2020b; Patwardhan 2005; Unschuld 1986).

A literature survey has shown that several families of plants have been used for medicinal purposes and in the development of new drugs. Some of the important medicinal plants are frequently obtained from Rutaceae, Asteraceae, Apocynaceae, Solanaceae, Caesalpiniaceae, Liliaceae, Piperaceae, Ranunculaceae, Apiaceae, Sapotaceae, Orchidaceae, and many more (Nautiyal et al. 2002; Husen and Rahman 2003; Husen and Faisal 2005; Aftab 2019). Aspirin, atropine, artemisinin, colchicine, digoxin, ephedrine, morphine, physostigmine, pilocarpine, quinine, quinidine, reserpine, taxol, tubocurarine, vincristine, vinblastine, etc., are important drugs obtained from the various medicinal/herbal plants. These drugs are obtained from the whole plant, leaves, roots, shoots, flower, or bark, etc. (Parveen et al. 2020a). For example, the root of *Rauvolfia serpentina* (Apocynaceae) is used to isolate serpentine, which is useful in the treatment of hypertension. Similarly, *Catharanthus roseus* is a source of vinblastine used in the treatment of different types of cancer (Iqbal and Srivastava 1997).

Numerous medicinal plants and their parts are a good source of bioactive compounds and/or secondary metabolites (terpenoids, phenolics, and nitrogen-based compounds) and have made a lot of contributions in drug formulation for the treatment of chronic diseases, such as heart disease, cancer, and diabetes (Iqbal 2013). Additionally, many other bioactive compounds obtained from herbal plants and combined with other compounds have shown to enhance the biological activity and are used in drug formulation (Kennedy and Wightman 2011; Shariff 2001). Generally, the significance of medicinal plants depends on the content and production of secondary metabolites. Swift et al. (2004) have reported over 100,000 known secondary metabolites with diverse chemical structures and function. Several factors such as harvest time, seasons, soil type, nutrient supply, altitude, geographical location, stage of plant (juvenile or mature stage), genotypes or cultivars, biotic stress, and abiotic stress (such as temperature variation, drought, salinity, and light intensity) extensively affect various plant processes including plant growth and development, and synthesis, accumulation, and production of secondary metabolites (Arshi et al. 2006a, b; Berini et al. 2018; Chetri et al. 2013; Falk et al. 2007; Iqbal et al. 2018; Ramakrishna and Ravishankar 2011; Zykin et al. 2018). Extraction process may also influence the chemical composition of natural products (Bucar et al. 2013; Jones and Kinghorn 2012). Like food crops and other higher plants, the medicinal plants also cope up with the surrounding adverse environment by producing secondary metabolites which help them to adopt and/or tolerate the stress situations (Berini et al. 2018; Isah 2019; Kroymann 2011). Several secondary metabolites have shown a specific role in defense against herbivores, pests, and pathogens (Bennett and Wallsgrove 1994; Zaynab et al. 2018) (Fig. 19.1). Accordingly, this chapter aims at reviewing the information about the secondary metabolites obtained from medicinal plants, their variation at different developmental stages, and the overall impact of adverse environmental conditions on their production.

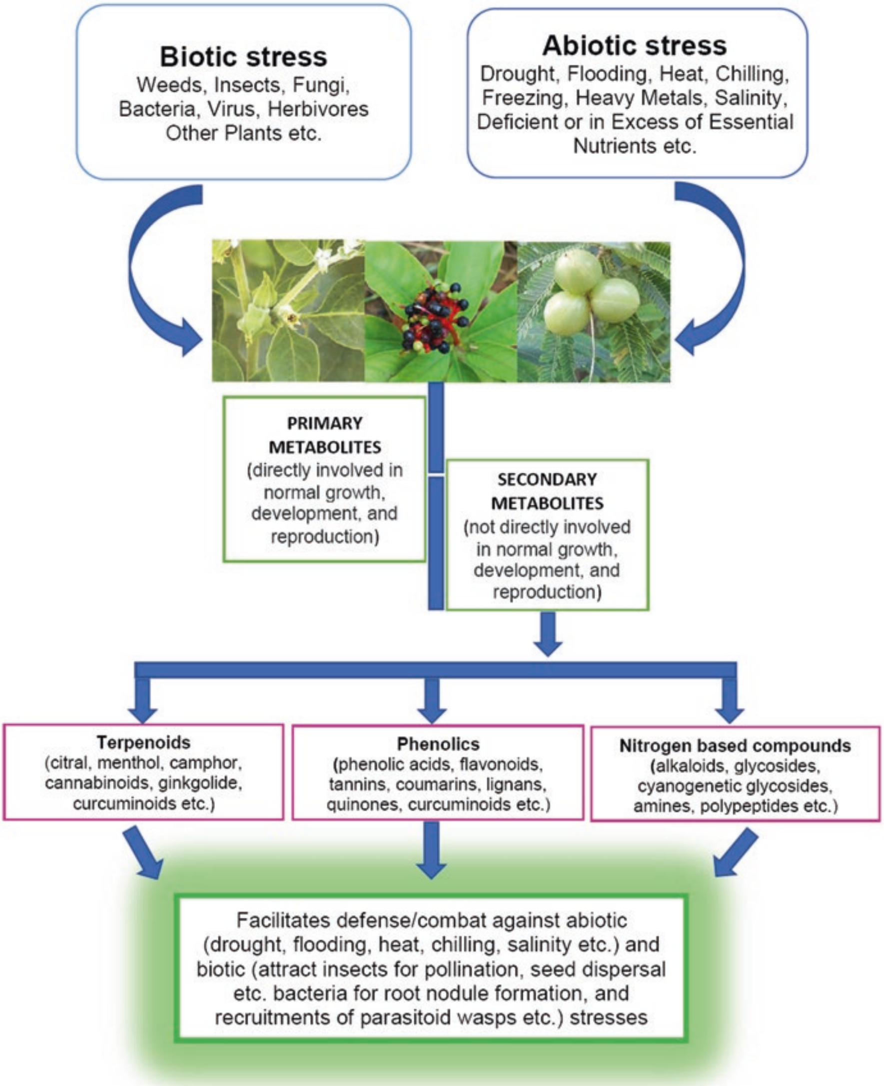

Fig. 19.1 Secondary metabolites under adverse environmental conditions and their role in plant defense

2 Secondary Metabolites and Their Production Sites

Herbal medicine is receiving attention in both developed and developing countries because of its natural origin and minimal adverse effects (Lawal and Yunusa 2013; Parveen et al. 2020b). The World Health Organization (WHO) report revealed that over nearly 80% of the global population uses herbal plants to cure human ailments (WHO 2019). Phytochemicals (natural products) are produced by plants via primary and/or secondary metabolism (Huang et al. 2016). They have shown various biological activities and play a key role in plant communication, growth, or defense against competitors, pathogens, or predators (Bachheti et al. 2019; Molyneux et al. 2007). Based on their biosynthetic pathway, secondary metabolites can be categorized into three major groups – phenolic compounds, terpenes, and nitrogen-containing compounds (Fang et al. 2011; Parveen et al. 2020b).

The flavonoids constitute one of the most widespread groups of natural products and are important to humans because they contribute color to plants and many of them, namely, coumestrol, phloridzin, rotenone, rutin, and artemetin. Flavonoids that occur as aglycones, glycosides (O-glycosides and C-glycosides), dimers, and methylated derivatives are physiologically active (Jay et al. 1975; Swain 1976). Glucose is the common sugar present in the flavonoids glycoside although the presence of galactose, rhamnose, xylose, arabinose, mannose, fructose, and apiose is also reported in mono-, di-, or tri-flavonoid glycosides (Harbone and Mabry 1975; Markham 1982). Structurally, flavonoids are benzo-y-pyrone derivatives that resemble coumarin. All the flavonoid aglycones consist of a benzene ring (A) condensed with a six-membered heterocyclic ring (C), which is either a γ-pyrone (chromone) or its dihydro derivative (4-chromone). The 4-chromone substituted by an aryl ring (B) at 2-position gives flavones and dihydroflavonols, and a similar substitution of chromone by aryl ring divides the flavonoids class into flavonoids (2-position) and isoflavonoids (3-position). Flavonols differ from flavanones by OH-group in the 3-position and a double bond at C2–C3 (Fig. 19.2). The common substituents such as free OH and OMe (methoxy group) are reported in flavonoids. In the case of O-glycosides, the C1 of sugar moiety is linked to flavonoid unit through O-atom. A free ortho position to phenolic hydroxyl groups appears to be a common feature that is a prerequisite for the formation of a C-glycosidic linkage in flavonoid (Markham 1982). In different classes of flavonoid C-glycosides (Fig. 19.1), the sugar moiety is attached directly to the ring A by C–C bond and is resistant to acid and enzymatic hydrolysis even after prolonged acid treatment, although partial isomerization often takes place under these conditions.

Terpenoids cover the major and most extensive group of natural plant products, and over 20,000 such structures have been described from plant sources. Isoprene a five-carbon unit, that is, isoprene, is the precursor of all terpenoids. Biosynthetically, they are formed in vivo by the condensation of two C_5 precursors, that is, dimethylallyl pyrophosphate and isopentenyl pyrophosphate (IPP), which give rise to C_{10}-intermediate, geranyl pyrophosphate (GPP). This is the immediate precursor of the monoterpenoids and the related monoterpene, and lactones are known as iridoids. GPP can be condensed in turn with another C_5 unit of IPP to produce the C_{15} intermediate, farnesyl pyrophosphate (FPP). This compound is the starting point for the synthesis of sesquiterpenoids. FPP can undergo further extension by linking with another IPP residue to produce the C_{20} intermediate, geranyl-geranyl pyrophosphate (GGPP). This is the general precursor of all the plant diterpenoids with their C_{20} base structures. Two molecules of the intermediate FPP can condense together in a further step in terpenoid biosynthesis with the formation of squalene, the C_{30} precursor of the largest group of isoprenoids, the triterpenoids. Two molecules of GGPP may condense together tail to tail to form a C_{40} intermediate called phytene, which

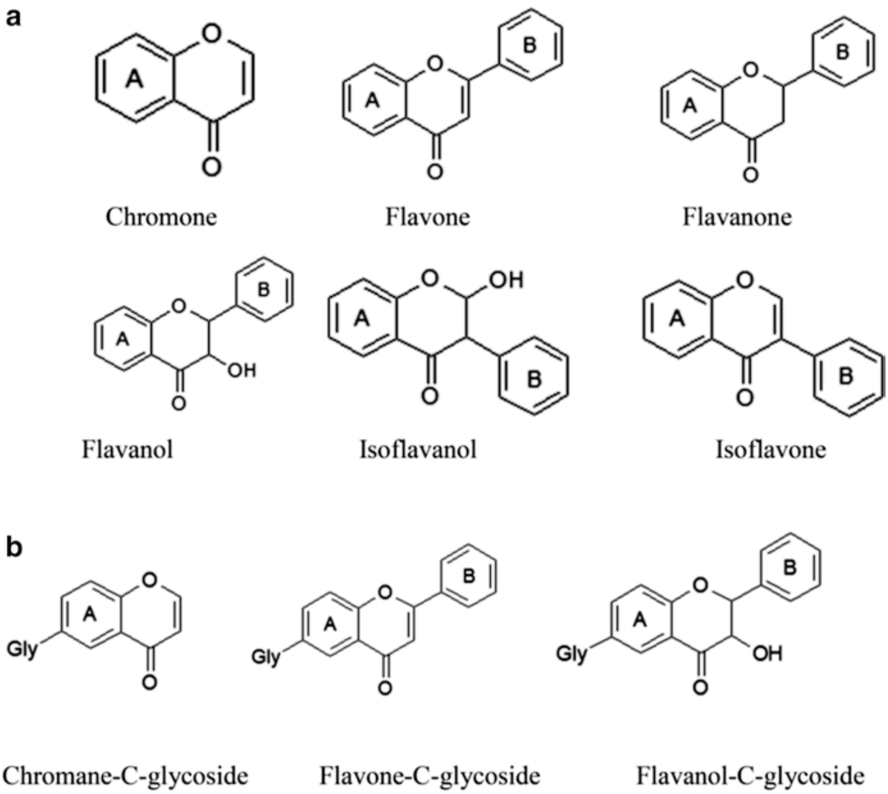

Fig. 19.2 Basic skeleton of natural occurring (**a**) flavonoid glycosides and (**b**) C-glycoside

is the immediate precursor of the yellow carotenoid pigments. The whole class of terpenoids is thus structurally very complex. Polymerization of IPP can occur in plants leading to polymer, which is commonly secreted in special cells as milky latex. Terpenoids have been classified into different classes such as monoterpenoids, sesquiterpenoids, diterpenoids, sesterterpene, and triterpenoids (Fig. 19.3) (Harborne 1998; Nakanishi et al. 1974).

Nitrogen-containing secondary metabolites contain alkaloids, cyanogenic glycosides, and glucosinolates. Alkaloids contain more than 12,000 nitrogen-containing low-molecular-weight compounds family (Facchini 2001; Khan and Rahman 2017) and are known for their biological activities. Examples of alkaloids are quinine, antineoplastic agents (camptothecin and vinblastine), and strychnine (poison for rats). Precursors for the biosynthesis of alkaloids include tyrosine, lysine, and tryptophan (Khalil 2017; Taiz and Zeiger 2006).

The growth and developmental stage (juvenile or mature phase) of medicinal plants, harvest times, etc. affect the production of secondary metabolites (Table 19.1). The major production sites of secondary metabolites are leaves, flowers, fruits and seeds, roots, and stem. Leaves produce food for plants by the process of photosynthesis. Also, it is used for synthesis and storage site for secondary metabolites. The

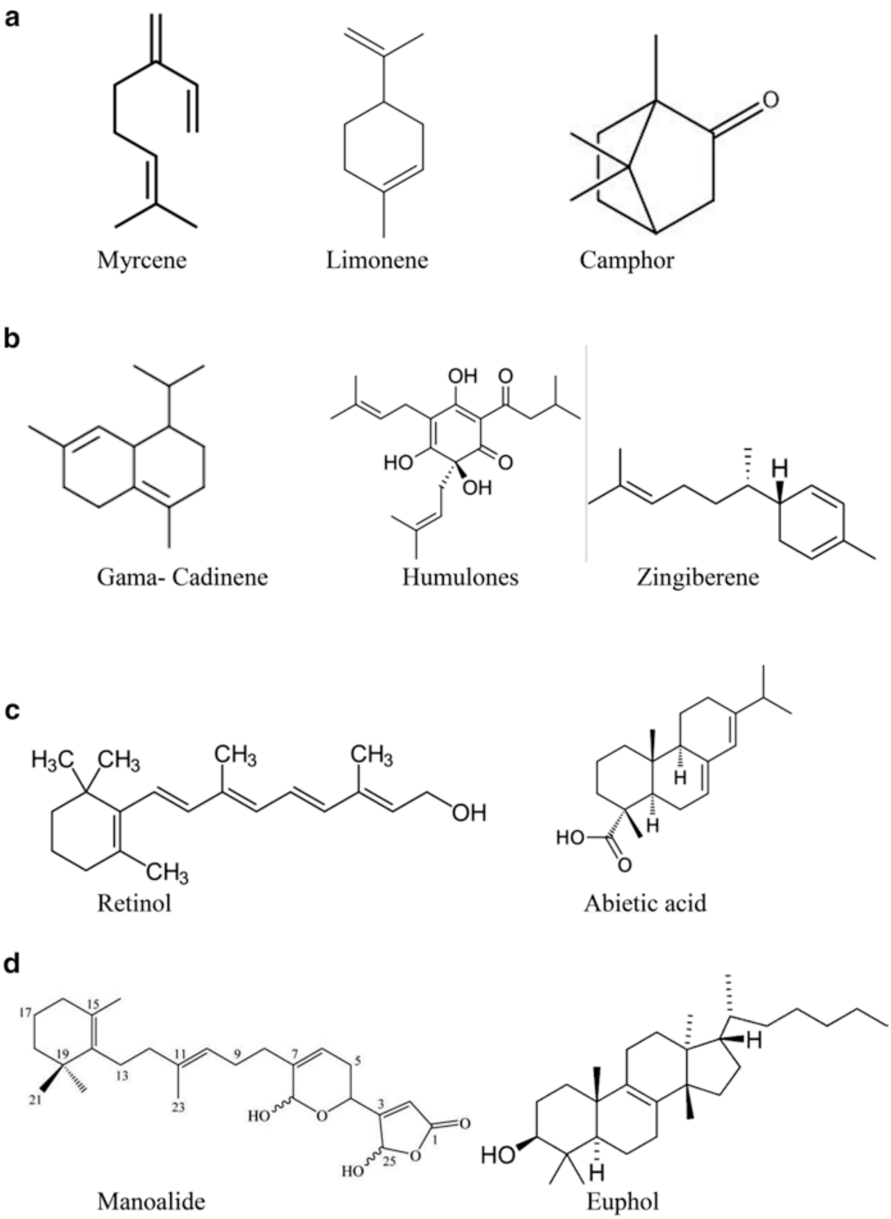

Fig. 19.3 Structures of naturally occurring terpenoids. (**a**) Monoterpenoids, (**b**) sesquiterpenoids, (**c**) diterpenoids, (**d**) sesterterpenoids, (**e**) triterpenoids

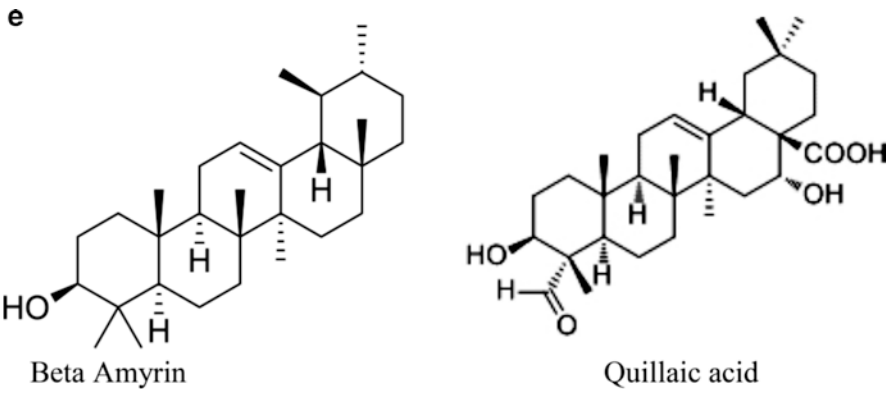

Fig. 19.3 (continued)

amount and/or concentration of secondary metabolites in plant leaves are usually affected by harvesting season, leafage, growth stage, etc. (Gomes et al. 2019; Li et al. 2016b; Vazquez-Leon et al. 2017). For instance, it was found that biosynthesis of terpenes (monoterpenes and sesquiterpenoids) starts at cotyledon stage of *Melaleuca alternifolia* (Southwell and Russell 2002). The highest content of essential oil (eugenol) in *Cinnamomum verum* was present in a 1-year-old leaf (Li et al. 2016b). However, in some plants, synthesis of compounds starts in the mature leaves. For instance, compounds associated with the sabinene hydrate–terpinen-4--ol–γ-terpinene pathways seem to be formed at later stages of development (Southwell and Russell 2002).

Normally, flowers have a good smell due to the presence of terpenes and aromatic compounds in them; their synthesis and storage are also affected by different developmental stages (Srivastava and Iqbal 1994). A study on volatile oils content of flower buds of *Magnolia zenii* at different growth stages found a remarkable difference in oil content at different growth stages (Hu et al. 2015). Volatile oil yield first increases and then decreases with the growth of flower buds, while maximum oil yield was obtained in October (Hu et al. 2015). Figueiredo et al. (2008) reported that the content of 1,8-cineole and camphor increases with the development stage of the flowers of *Achillea millefolium,* while the content of azulene decreases. In the case of *Antirrhinum majus,* contents of ocimene and elemene quickly increased on the second day after flowering and decreased after attaining peak on the sixth day (Dudareva et al. 2003). The developmental stages of fruit and seed also have a remarkable influence on the secondary metabolites content and composition. A study by Liang et al. (2006) has shown that the highest amount of essential oils (volatile oil) is present in citrus fruit when it is light yellow. Wu et al. (2013) also reported that the yield of essential oil increased the maturation process and the contents of β-pinene, α-thujone, carene, and γ-terpinene in *Citrus medica* change significantly during the maturation stage. Also, the maximum content of morphine was reported at the maturity of *Papaver somniferum* roots (Shukla and Singh 2001). The content of dicoffee quinic acids decreases with the developmental stage, while the content of quinic acid was the highest in the early developmental stage in coffee seeds (Lepelley et al. 2007). The highest saponins content in the root of *Panax notoginseng* was found when the plant was 3-year-old (Hong et al. 2005). Further details are presented in Table 19.1.

3 Role of Secondary Metabolites Under Adverse Environment

During the entire life span, plants come across both abiotic and biotic stresses. Secondary metabolites exhibit a significant role in tolerance and adaptation of plants to adverse environmental conditions (Anjum et al. 2014). Additionally, the biosynthesis of secondary metabolites is also influenced under various environmental conditions (Iqbal et al. 2011). Further details of different types of stresses encountered by the plant are shown in Fig. 19.1.

3.1 Biotic Stress

Like crop plants, medicinal plant growth and production are also affected by potential biotic enemies, such as bacteria, viruses, fungi, nematodes, mites, insects, mammals, and other herbivorous animals. Due to sessile nature, plants are unable to change their position to get rid of such enemies. In this negative situation, they protect themselves by producing secondary metabolites. For instance, phytoalexins having antimicrobial activity are produced by plants on attack of pathogen (Taiz and Zeiger 2006). Similarly, Verma and Shukla (2015) have reported that when a plant undergoes fungal infections, significant variation occurs in phenolics content. Kim et al. (2008) have reported that among the various secondary metabolites, the phenolic compounds play a vital role in plant defense against pathogens and insects attack. Alkaloids are also involved in plant defense and are produced in response to attacks by a microorganism (Joosten and van Veen 2011). It has been also reported that the content of trigonelline, camptothecin, and castanospermine increased due to reactions with fungus inoculum (Jia et al. 2016). Some specific enzymes are capable of avoiding the attack of any unsuitable organisms. For instance, the activity of polyphenol oxidase increases in wounded plants attacked by pests or infected by pathogens (Vanitha et al. 2009). Some plants also produce o-quinones, which act as antimicrobial agents and protect plants (Constabel et al. 2000).

Table 19.1 Secondary metabolites changes at various developmental stages in some medicinal plants

Medicinal plant (family)	Plant part	Developmental stage	Major class of secondary metabolite/ bioactive compounds	Name of metabolite	Concentration variation	Key references
Mentha × piperita (Lamiaceae)	Plants	Matured plant	Terpenoids	Menthofuran, limonene, and pulegone	Decreased as plant matured	Abdi et al. (2019)
Mentha × piperita (Lamiaceae)	Plants	Matured plant	Terpenoids	Menthol, cineole, and neomenthol	Increased as plant matured	Abdi et al. (2019)
Lonicera japonica (Caprifoliaceae)	Flower	Whole growth stage	Phenols	Chlorogenic acid	Increasing first and then decreasing	Li et al. (2019); Kong et al. (2017)
Scutellaria baicalensis (Fabaceae)	Root	Before the full-bloom stage	Flavonoids	Flavonoids	Strong increase	Xu et al. 2018
Cinnamomum verum (Lauraceae)	Leaf	1-year-old	Phenols	Eugenol	Highest	Li et al. (2016b)
Magnolia zenii (Magnoliaceae)	Flower bud	October	Terpenoids	Essential oils	Highest	Hu et al. (2015)
Codonopsis pilosula (Campanulaceae)	Root	Older tree	Terpenoids	Triterpene	Low	Zhu et al. (2014)
Cinnamomum cassia (Lauraceae); *Cinnamomum verum* (Lauraceae)	Leaf	2-year-old branch	Terpenoids	Essential oils	Highest	Li et al. (2013)
Citrus medica (Rutaceae)	Fruit	Maturation process	Terpenoids	Essential oils	Significant increase	Wu et al. (2013)
Magnolia officinalis (Magnoliaceae)	Bark	13-year-old	Flavonoids	Hyperin and quercetin	Highest	Yang et al. (2012)
Magnolia officinalis (Magnoliaceae)	Bark	7-year-old	Flavonoids	Rutin and quercitrin	Highest	Yang et al. (2012)

(continued)

Table 19.1 (continued)

Medicinal plant (family)	Plant part	Developmental stage	Major class of secondary metabolite/ bioactive compounds	Name of metabolite	Concentration variation	Key references
Scutellaria baicalensis (Lamiaceae)	Root	Whole growth stage	Flavonoids	Baicalin	Increases and then gradually decreases	Hu et al. (2012)
Magnolia officinalis (Magnoliaceae)	Bark	13-year-old	Phenols	Chlorogenic acid	Highest	Yang et al. (2012)
Cinnamomum cassia (Lauraceae)	Stem and bark	Increased years	Terpenoids	Essential oils	Increase	Geng et al. (2011)
Allium sativum (Alliaceae)	Bulb	Late planting during December	Organosulfur compound	Alliin, allicin, allyl sulfide, (E)-ajoene, and (Z)-ajoene	Higher	Montaño et al. (2011)
Allium sativum (Alliaceae)	Bulb	Late harvesting	Organosulfur compound	Alliin	Higher	Belguith et al. (2010)
Rosa × *hybrid* (Rosaceae)	Flower	Fully open flowers	Flavonoid	Anthocyanin	Increased from bud stage to fully open flowers, and decreased in senescent ones	Schmitzer et al. (2010)
Rosa × *hybrid* (Rosaceae)	Flower	Fully open flowers	Flavonoid	Quercetin	Increased from bud stage to fully open flowers, and decreased in senescent ones	Schmitzer et al. (2010)
Rosa × *hybrid* (Rosaceae)	Flower	In buds or partially open flower stage	Total phenolics	Phenolics	Highest content	Schmitzer et al. (2010)
Achillea millefolium (Asteraceae)	Flower	With the development of the flowers	Terpenoids	Camphor and 1,8-cineole	Increase	Figueiredo et al. (2008)
Citrus medica (Rutaceae)	Fruit	Fruit is light yellow	Terpenoids	Essential oils	Highest	Liang et al. (2006)

3.2 Abiotic Stress

Climate change and an environmental variation, such as temperature, drought, salinity, solar radiation, and air pollution, have been reported to affect the production of secondary metabolites (De Castro et al. 2020; Ferreira et al. 2016; Iqbal et al. 2018; Kulak et al. 2020; Nascimento et al. 2015; Qureshi et al. 2013; Sampaio et al. 2016; Sharma et al. 2019; Zhou et al. 2017). Some of the major abiotic stress conditions and plant response in terms of secondary metabolite production are discussed in the following.

3.2.1 Temperature Stress

Change in temperature affects plant growth and secondary metabolite content due to changes in the metabolic pathways that control physiology, signaling, and defense mechanisms. Studies have shown that the production of secondary metabolites increases in response to elevated temperatures in *Pringlea antiscorbutica* (Hummel et al. 2004) and *Panax quinquefolius* (Jochum et al. 2007). However, in the case of *Pseudotsuga menziesii*, high temperature has reduced the content of monoterpene (Snow et al. 2003). Some studies such as Ruelland et al. (2009) and Sevillano et al. (2009) have suggested that low temperature generates reactive oxygen species (ROS), and to neutralize their effect, the plant generates antioxidative enzymes. However, almost all the abiotic stresses, including high- and low-temperature stresses, cause oxidative damage and generate ROS in plants (Aref et al. 2016; Siddiqi and Husen 2017, 2019). Thus, plants evolved a range of tolerance mechanisms to manage the damage produced by these stresses, such as activation of antioxidative enzymes, and the accumulation of compatible solutes that effectively scavenge ROS. The chemical composition of essential oil has also been affected due to changes in temperature conditions. For instance, the effect of cold temperature on essential oil composition *Origanum dictamnus* was examined by Lianopoulou and Bosabalidis (2014). This investigation has shown that the main components of essential oil of *Origanum dictamnus* were p-cymene, carvacrol, γ-terpinene, and borneol; however, in winter, content of p-cymene was 59.2%, whereas in summer, carvacrol content was 42%. Low temperature increases the accumulation of withanolides (steroids) in the leaves of *Withania somnifera* (Khan et al. 2015; Kumar et al. 2012). Also, in transgenic plants of this species, the same trend was noticed when exposed to low temperature, that is, increase in withanolide content when plant exposed to low temperature (Saema et al. 2016). Rivero et al. (2001) studied the effect of high temperature on tomato plants and found that high temperature causes accumulation of phenolic contents. Wu et al. (2016) studied polyphenols in different sorghum genotypes under high-temperature stress. They have suggested that the brown sorghum was rich in phenolic profile, and thus exhibited a greater temperature tolerance. Further details associated with medicinal plants and their response under temperature stress are given in Table 19.2.

Table 19.2 Medicinal plants and their response under temperature stress

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Temperature stress	Concentration variation	Key references
Mentha piperita (Lamiaceae)	Leaves	To treat flatulence, menstrual pains, depression-related anxiety, muscle, nerve pain, etc.	Total phenol, flavonoid, and saponin	–	Heat stress	Decrease	Haifa et al. (2019)
Catharanthus roseus (Apocynaceae)	Leaves	Used for relieving muscle pain, depression of CNS, also for applying to wasp stings and in wound healing	Total phenol, flavonoid, and saponin	–	Heat stress	Decrease	Haifa et al. (2019)
Camellia japonica (Theaceae)	Leaves	Used as astringent, antihemorrhagic, hemostatic, salve, tonic, etc.	Tannins, terpenoids, and alkaloids	–	Low temperature	Increase	Li et al. (2016a)
Aquilaria sinensis (Thymelaeaceae)	Plant cells	Used against cancer, abdominal pains, asthma, colic, and diarrhea	Terpenes	Sesquiterpene-α-humulene, α-guaiene, and δ-guaiene	Heat shock	Increase	Xu et al. (2016)
Camellia japonica (Theaceae)*Astragalus compactus* (Fabaceae)	Leaves, roots, and flowers	Used as astringent, antihemorrhagic, hemostatic, salve, tonic, etc. Used as anti-inflammatory, immunostimulant, antioxidative, anticancer, antidiabetic, cardioprotective, hepatoprotective, and antiviral	Fatty acids	α-Linolenic acid and jasmonic acid	Low temperature and high temperature	Increase	Li et al. (2016a); Naghiloo et al. (2012)
			Phenols	Phenolics		Increase	

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Temperature stress	Concentration variation	Key references
Astragalus compactus (Fabaceae)	Roots, leaf, and flowers	Used as anti-inflammatory, immunostimulant, antioxidative, anticancer, antidiabetic, cardioprotective, hepatoprotective, antiviral, etc.	Tannins, terpenoids, and alkaloids	–	High temperature	Increase	Naghiloo et al. (2012)
Artemisia annua (Asteraceae)	Whole plant	Used in fever, liver disease, depression, muscle pain, and memory loss	Sesquiterpene lactone	Artemisinin	A transient prechilling treatment	Increase	Yin et al. (2008)
Panax quinquefolius (Araliaceae)	Roots	Used to boost energy, lower BP and cholesterol levels, reduce stress, promote relaxation, treat diabetes, manage sexual dysfunction in men, etc.	Saponins	Ginsenoside	Heat stress	Increase	Jochum et al. 2007
Beta vulgaris (Amaranthaceae)	Root	Improve blood flow, lower blood pressure, etc.	Flavonoid	Anthocyanin	50 °C temperature	Decreases	Thimmaraju et al. (2003)
Perilla frutescens (Lamiaceae)	Cultured cells	Used for cure of asthma and cough, etc.	Flavonoid	Anthocyanins	Heat stress	Decrease	Zhong and Yoshida (1993)
Chrysanthemum (Asteraceae)	Whole plant	Used to treat chest pain (angina), high blood pressure, type 2 diabetes, fever, cold, headache, dizziness, swelling, etc.	Phenols	Anthocyanins	High temperature	Decrease	Shibata et al. (1988)

3.2.2 Drought Stress

Global climate change is increasing the frequency of severe drought conditions. Drought stress conditions affect adversely growth, development, and the overall physiological and biochemical status of plants (Embiale et al. 2016; Getnet et al. 2015; Husen 2010; Husen et al. 2014). Similarly, drought stress affects the production of secondary metabolite contents (Caser et al. 2019; Podda et al. 2019). Plants accumulate more secondary metabolites in water-stressed conditions and a decrease in biomass production (Kleinwächter and Selmar 2014). A study was performed on *Adonis amurensis* and *A. pseudoamurensis* to check the effect of drought on secondary metabolites and changes in growth and physiology. In the early stage, both the perennial plants showed an adaptive change to drought stress and a significant increase in flavonoids and total phenols content in response to drought stress (Gao et al. 2020). In another study, García-Caparrós et al. (2019) observed the impact of drought stress on the essential oil content of *Lavandula latifolia*, *Mentha piperita*, *Salvia sclarea*, *S. lavandulifolia*, *Thymus mastichina*, and *T. capitatus*. The essential oil content of *Lavandula latifolia* and *Salvia sclarea* plants showed a reduction under drought stress conditions. Chavoushi et al. (2020) examined *Carthamus tinctorius* and found that secondary metabolites (flavonoids, anthocyanin, phenol, and phenylalanine ammonia-lyase activity) increased under drought stress conditions. Drought stress also increased the concentration of monoterpene in *Salvia officinalis* (Nowak et al. 2010), and its concentration was more than the reduction in biomass as compared to control plants. A similar type of result (increases in monoterpenes concentration and biomass reduction) was observed in another experiment conducted on *Petroselinum crispum* under drought stress condition (Petropoulos et al. 2008). An increase in secondary metabolites content of total anthocyanins, phenolics, and total flavonoids was also observed in *Labisia pumila* when it was kept under high water stress conditions (50% evapotranspiration) (Jaafar et al. 2012). Further details associated with medicinal plants and their responses to drought stress are given in Table 19.3.

3.2.3 Salinity Stress

Salinity stress is another important global problem that negatively affects plant growth and production (Husen et al. 2016, 2018, 2019; Hussein et al. 2017; Isayenkov and Maathuis 2019). It also affects the accumulation of secondary metabolites in plant tissues (Arshi et al. 2002; Cui et al. 2019; Hakeem et al. 2013; Ibrahim et al. 2019; Wang et al. 2015). In *Gossypium hirsutum*, salinity stress enhanced the secondary metabolism as indicated by the increased accumulation of gossypol, flavonoids, and tannin (Wang et al. 2015). Germination of *Prosopis strombulifera* seed was severely affected by increased salinity (Sosa et al. 2005). Further, seed germination of some other medicinal plants decreases under salt stress, as in *Ocimum basilicum* (Miceli et al. 2003), *Petroselinum hortense* (Ramin 2005), and *Thymus maroccanus* (Belaqziz et al. 2009). Seedling growth is also negatively affected by

Table 19.3 Medicinal plants and their response under drought stress

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Drought stress	Concentration variation	Key references
Hordeum vulgare (Poaceae)	Leaves	Used in the treatment of dyspepsia caused by cereals, infantile lacto-dyspepsia, regurgitation of milk and breast distension	Terpenes	Carotenoids	Severe drought condition	Decreases	Ghorbanpour et al. (2020)
Salvia dolomítica (Lamiaceae)	Leaves	Used in seizure, ulcers, gout, rheumatism, tremor, paralysis, and hyperglycemia	Phenols and total flavonoids	Sesquiterpene and terpenoids	Irrigation	Increases	Caser et al. (2019)
Achillea pachycephala (Asteraceae)	Leaves	Treatment of wounds, bleedings, headache, inflammation, pains, spasmodic diseases, flatulence, and dyspepsia	Flavonoids and phenolic compound	Luteolin and apigenin, chlorogenic acid, and caffeic acid	Irrigation	Increases	Gharibi et al. (2019)
Dracocephalum moldavica (Lamiaceae)	Shoot	Antioxidation and antiaging	Phenolic acids, ellagitannins, and flavonoids	Rosmarinic acid, chlorogenic acid, p-coumaric acid, caffeic acid, ferulic acid, apigenin, acacetin 7-O-glycoside, gentisic acid, apigenin-7-O-glycoside, luteolin-7-O-glycoside, and quercetin	Irrigation	Increase	Kamalizadeh et al. (2019)

(continued)

Table 19.3 (continued)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Drought stress	Concentration variation	Key references
Datura stramonium (Solanaceae)	Whole plant	Used as analgesic, anthelmintic, anti-inflammatory, to treat toothache, dandruff, and hair fall	Alkaloids	Atropine and scopolamine	Severe water deficit stress	Increases	Alinejad et al. (2020)
Mentha piperita (Lamiaceae)	Leaves	To treat flatulence, menstrual pains, depression-related anxiety, muscle, and nerve pain	(i) Total phenol, flavonoid, and saponin (ii) Tannins, terpenoids, and alkaloids	– –	Drought	Decreases Increases	Haifa et al. (2019)
Catharanthus roseus (Apocynaceae)	Leaves	Used for relieving muscle pain, depression of CNS, also for applying to wasp stings and to heal wounds	(i) Total phenol, flavonoid, and saponin (ii) Tannins, terpenoids, and alkaloids	– –	Drought	Decreases Increases	Haifa et al. (2019)
Thymus kotschyanus (Lamiaceae)	Seedling	Used as antibacterial, antifungal, antiviral, antihelminthic, antioxidative, antispasmodic, and sedative	Phenols and monoterpenoids	Thymol, carvacrol, linalool, p-cymene, and γ-terpinene	Water stress	Increases	Mohammadi et al. (2018)
Scutellaria baicalensis (Lamiaceae)	Whole plant	Used in epilepsy, hepatitis, infections, and cancer	Phenols	Baicalin	Severe drought condition	Increases	Cheng et al. (2018)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Drought stress	Concentration variation	Key references
Salvia sinaloensis (Lamiaceae)	Leaves	Digestive problems	Phenols and total flavonoids	–	Irrigation	Increase	Caser et al. (2018)
Ocimum basilicum (Lamiaceae)	Shoot	Used as antioxidant antimicrobial, antiviral, cytoprotective, anticonvulsant, hypoglycemic, hypolipidemic, hepatoprotective, renoprotective, neuroprotective, spermicidal, dermatologic, and insecticidal	Total phenols	–	Irrigation	Increases	Pirbalouti et al. (2017)
Stellaria dichotoma (Caryophyllaceae)	Roots	Used in fever and malaria, night sweats, and infantile malnutrition	Total flavonoids	–	(i) Moderate drought stress (ii) Severe drought stress	(i) Increases (ii) Decreases	Zhang et al. (2017)
Melissa officinalis (Lamiaceae)	Shoot	Used in gastrointestinal disorders and as sedative	Phenolic compounds	Hydroxycinnamic acid	Irrigation	Decreases	Szabo et al. (2017)
	Leaves		Total flavonoids and phenolic compound	Rosmarinic acid			Radacsi et al. (2016)

(continued)

Table 19.3 (continued)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Drought stress	Concentration variation	Key references
Mikania glomerata (Asteraceae)	Leaves	For respiratory illness	Phenolic acids	Chlorogenic acid and dicaffeoylquinic acid	Water deficiency	Increases	Almeida et al. (2016)
Cuminum cyminum (Apiaceae)	Leaves	For chronic diarrhea and dyspepsia, acute gastritis, diabetes, and cancer	Flavonoids and phenolics	–	150 mm irrigation regime	Increases	Alinian et al. (2016)
			Flavonoid	Anthocyanins	200 mm irrigation regime	Increases	
	Seeds		Flavonoids and phenolics	–	200 mm irrigation regime	Increases	
Helichrysum petiolare (Asteraceae)	Leaves	Used for respiratory infections, diabetes, fever, headache, heart problem, high blood pressure, pain, and reproductive problems	Flavonoids and polyphenol	Anthocyanins	Moderate drought stress	Increases	Caser et al. (2016)
Anadenanthera colubrina (Fabaceae)	Bark	Used for respiratory problems and inflammation	Phenolic compounds	–	Precipitation	No effect	Araujo et al. (2015)
Gethyllis multifolia (Amaryllidaceae)	Leaves	For wound healing	Tannin, flavonoids, phenolics, saponins, and terpenoid	Flavonol and flavanone	Drought stress	Present	Daniels et al. (2015)
	Roots		Polyphenol			Increases	

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Drought stress	Concentration variation	Key references
Hypericum brasiliense (Hypericaceae)	Whole plant	Used as astringent, antimicrobial, wound-healing, anticancer, anti-inflammatory, antispasmodic, and antidepressant	Phenols and pentacyclic triterpenoid	Rutin, quercetin and betulinic acid	Severe drought condition	Increases	Verma and Shukla (2015)
Artemisia spp. (Asteraceae)	Whole plant	Used in fever, liver disease, depression, muscle pain, and memory loss	Sesquiterpene lactone	Artemisinin	Severe drought condition	Increases	Verma and Shukla (2015)
Achillea millefolium (Asteraceae)	Leaves	For treating wounds, stopping the flow of blood, treating colds, fevers, kidney diseases, and menstrual pain	Total phenolic and total flavonoid	–	Moderate drought stress	Increases	Gharibi et al. (2015)
Astragalus propinquus (Fabaceae)	Roots	Used for immune-boosting, antiaging, and anti-inflammatory, used to treat fatigue, allergies, heart disease, and diabetes	Flavonoids	Calicosin-7-O-b-D-glycoside, ononine, calicosin, and formononetine	Drought stress	Increases	Jia et al. (2015)

(continued)

Table 19.3 (continued)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Drought stress	Concentration variation	Key references
Petroselinum crispum (Apiaceae)	Shoots	Used as a diuretic, antimicrobial, antiseptic, antispasmodic, and for kidney stone	Flavones	Malonylapiin, diosmetin apiosylmglucoside, and diosmetin malonyl-apiosyl-glucoside	Moderate drought stress	Decreases	Kleinwächter et al. (2015)
			Essential oil			Increases	
Hypericum polyanthemum (Hypericaceae)	Leaves and reproductive parts	Used as antidepressant, antiviral, antinociceptive, antimicrobial, antipyretic, and anti-inflammatory	Phenolic compounds	Uliginosin B (phloroglucinol), 6-isobutyryl-5,7-dimethoxy-2,2-dimethylbenzopyran and 5-hydroxy-6-isobutyryl-7--methoxy-2,2-dimethylbenzopyran (benzopyran) and total phenols	Drought stress	Increases	Nunes et al. (2014)
Eucalyptus globulus (Myrtaceae)	Leaves	Used as expectorant, febrifuge, tonic, astringent, antiseptic, hemostatic, and vermifugal	Total phenols	–	Moderate or severe drought stress	Decreases	McKiernan et al. (2014)
			All plant SMs	Total condensed tannins and two floroglucinols and terpenes		No effect	
Labisia pumila (Primulaceae)	–	Used for cardiovascular protection and osteoporosis	Phenols flavonoids	Total phenolics and anthocyanins	Severe drought condition	Increased	Jaafar et al. (2012)
Thymus vulgaris (Lamiaceae)	Shoot	Used for diarrhea, stomach ache, arthritis, and sore throat	Phenolic compounds	–	Long-term drought stress	Decreases	Khosh-Khui et al. (2012)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Drought stress	Concentration variation	Key references
Trachyspermum ammi (Apiaceae)	Leaves	Used as atonic dyspepsia, diarrhea, fominal tumors, abdominal pains, piles, and bronchial problems, asthma, antispasmodic, and carminative	Phenols	Total phenolics	Severe drought condition	Increases	Azhar et al. (2011)
Lippia sidoides (Verbenaceae)	Leaves	Used for cough, bronchitis, indigestion, liver, hypertension, dysentery, worms, and skin diseases	Total flavonoids and essential oil	–	Water stress	Decreases	Alvarenga et al. (2011)
Salvia miltiorrhiza (Lamiaceae)	Root	Used for coronary heart diseases and cerebrovascular diseases	Polyphenol	Rosmarinic acid	Drought stress	Decreases	Liu et al. (2011)
			Phenolic acid	Salvianolic acid B		Increases	
Nepeta cataria (Lamiaceae)	Whole plant	Used to treat intestinal cramps, indigestion and to induce menstruation	Essential oil	–	Drought stress	Increases	Manukyan (2011)
			Polyphenols	Caffeic acid, rosmarinic acid, and p-coumaric acid		Decreases	
Calendula officinalis (Asteraceae)	Leaves	Used to heal wounds, burns, and rashes	Flavonoids	–	Water deficiency	Decreases	Pacheco et al. (2011)

(continued)

Table 19.3 (continued)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Drought stress	Concentration variation	Key references
Salvia officinalis (Lamiaceae)	Whole plant	Used for seizure, ulcers, rheumatism, tremor, and paralysis	Terpenes	Monoterpenes	Severe drought condition	Increases	Nowak et al. (2010)
Petroselinum Crispum (Apiaceae)	Leaves	Plague and malaria	Terpenes	Monoterpenes	Severe drought condition	Increases	Petropoulos et al. (2008)
Rehmannia glutinosa (Orobanchaceae)	Roots	Used for diabetes, metabolic syndrome, obesity, kidney disease, chronic obstructive pulmonary disease (COPD), "tired blood" (anemia), fever, weakened bones (osteoporosis), rheumatoid arthritis (RA), and allergies	Phenolic compounds	Resveratrol, gentisic acid, catechin, p-hydroxybenzoic acid, chlorogenic acid, caffeic acid, syringic acid, coumaric acid, ferulic acid, hesperidin, narigin, salicylic acid, hyricetin, quercetin, t-cinnamic acid, and naringenin	Water deficiency	Increases	Chung et al. (2006)
Camellia sinensis (Theaceae)	Leaves	Used for cancer prevention, to lower cholesterol, and to prevent/delay Parkinson's disease, etc.	Phenols and polyphenols	Flavan-3-ols (epicatechin, epigallocatechin-3-gallate) and their quinones	Water stress	Increases	Hernández et al. (2006)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Drought stress	Concentration variation	Key references
Myracrodruon urundeuva (Anacardiaceae or Fabaceae)	Leaves	Used for kidney problems, hemoptysis, metrorrhagia, for postnatal vaginal washes, stomach ulcers, and colitis	Tannins	–	Precipitation	No effect	Monteiro et al. (2006)
	Bark					Negative correlation	
Hypericum brasiliense (Hypericaceae)	Roots and shoot	Used as anti-inflammatory, antibacterial, and antidepressant	Phenolic compound and betulinic acid	Isouliginosin B; 1,5-dihydroxyxanthone, quercetin, and rutin	Water stress	Increases	Abreu and Mazzafera (2005)
Crataegus laevigata (Rosaceae)	Leaves	Used for congestive heart failure, chest pain, irregular heartbeat, low BP, high BP, and high cholesterol	Polyphenolic compounds	Chlorogenic acid, catechin, and epicatechin	Water deficiency	Increases	Kirakosyan et al. (2004)
			Flavonoid	Vitexin, hyperoside, and rutin		Increases	
				Acetylvitexin-2″-O-rhamnoside		Decreases	
				Vitexin-2″-O-rhamnosid and quercetin		No effect	

salinity, as in basil (Ramin 2005), chamomile, and marjoram (Ali et al. 2007) and *Thymus maroccanus* (Belaqziz et al. 2009). There are inconsistent reports on the effect of salt stress on essential oil content. In some studies, a negative effect of salt stress in essential oil yield is noticed, as in *Trachyspermum ammi* (Ashraf and Orooj 2006), *Mentha piperita* (Tabatabaie and Nazari 2007), *Thymus maroccanus* (Belaqziz et al. 2009), and basil (Said-Al Ahi et al. 2010). In these cases, oil content decreased under salt stress conditions. Nonetheless, in *Matricaria recutita*, the main chemical constituents of essential oil such as α-bisabololoxide B, α-bisabolonoxide A, chamazulene, and α-bisabolol oxide A increased under salt stress conditions (Baghalian et al. 2008). In *Origanum vulgare,* the main chemical constituents of essential oil carvacrol were found to decrease in salt stress, whereas p-cymene and γ-terpinene content increase under normal condition (Said-Al Ahl and Hussein 2010). De Castro et al. (2020) observed the effect of salinity on essential oil profile, growth, and morphology in *Lippia alba* and found that increase in linalool and decrease in eucalyptol levels at higher salt stress conditions. Further details associated with medicinal plants and their response to salinity stress are given in Table 19.4.

3.2.4 Light Intensity

Light intensity determines the concentration of plant secondary metabolites (Jurić et al. 2020; Pedroso et al. 2017; Tavakoli et al. 2020; Thoma et al. 2020). Light may suppress or stimulate the production of various secondary metabolites depending on its quantity (intensity) or duration (photoperiod). Production of flavonoid, phenolic compound, and terpenoids in root and shoots of *Hordeum vulgare* got stimulated in the presence of full sunlight as well as in monochromatic light, that is, blue light (Klem et al. 2019). Similarly, the concentration of scutellarin (phenols) in leaves of *Erigeron breviscapus* increased in full sunlight (Zhou et al. 2016). Li et al. (2018) have also reported that the alkaloids concentration in root, shoots, and essential oils in leaves of *Mahonia breviracema* increases in the presence of full sunlight. This study also found that hexadecanoic acid in leaves increases when *Mahonia bodinieri* was grown under 50% stress of light availability. Also, Kong et al. (2016) examined some other parts of *Mahonia bodinieri* and concluded that under 30–50% stress, the alkaloid content get enhanced, and in the case of *Flourensia cernua*, the alkaloids content of leaves such as sabinene, β-pinene, borneol, bornyl acetate, and Z-jasmone was increased when half of the regular sunlight available for plants was provided, that is, in 50% light stress. Further details associated with medicinal plants and their response to light are given in Table 19.5.

3.2.5 Heavy Metal Stress

The secondary metabolites production in plants also gets affected by the presence of heavy metals (Iqbal et al. 2015; Jabeen et al. 2009). Various researchers have claimed this, such as Manquian-Cerda et al. (2016) reported that in the presence of

Table 19.4 Medicinal plants and their response under salinity stress

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Salinity	Concentration variation	Key references
Salvia officinalis L. (Lamiaceae)	Seeds	Used for secondary memory improvement, improve alertness, neurotoxic	Niacin, nicotinamide, and flavonoid glycosides	α-thujone, α-pinene, camphor, camphene, β-thujone, and 1,8-Cineole	Salt concentration increases	Essential oil composition get affected	Kulak et al. (2020)
Thymus maroccanus (Lamiaceae)	Whole plant	Used as antioxidant, antimicrobial, antitumor, and cytotoxic	Essential oil	Carvacrol, p-cymene, α-pinene, α-terpineol, and p-cymene	Salt stress	Decreases	Belaqziz et al. (2009)
Thymus vulgaris (Lamiaceae)	Shoot and leaves	Used for gastroenteric and bronchopulmonary disorders	Phenolic acids	Syringic, gallic, vanillic, caffeic, chlorogenic, rosmarinic, cinnamic, and trans-2-hydroxycinnamic acids	Salinity increases	Increase	Bistgani et al. (2019)
					Severe salinity	Not found	
Thymus daenensis (Lamiaceae)	Shoot and leaves	Used as anti-inflammatory, antimicrobial, and antioxidant	Flavonoid	Quercitrin, apigenin, luteolin, naringenin, and rutin	Salinity increases	Increase	Bistgani et al. (2019)
Mentha piperita L. (Lamiaceae)	Leaves	Used as carminative, spasmolytic, antitumor, antidiabetes, and antinociceptive	Flavonoids and phenols	Hesperidin, rosmarinic acid, didymin, buddleoside, and diosmin	Less salinity	SMs concentration increased	Çoban and Göktürk Baydar (2016)
Trigonella foenum graecum L. (Fabaceae)	Leaves	Used as aphrodisiac, carminative, astringent, demulcent, suppurative, aperients, diuretic, emollient, anti-inflammatory, etc.	Total phenolic content and flavonoids	Phenols and diosgenin	Salinity increases	Increases	Baatour et al. (2018)

(continued)

Table 19.4 (continued)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Salinity	Concentration variation	Key references
Catharanthus roseus (Apocynaceae)	Leaves	Used to treat cancer	Vinca alkaloid	(i) Vinblastine (ii) Vincristine	(i) Salinity increases (ii) Salinity increases	(i) Increases (ii) Decreases	Fatima et al. (2015)
Stevia rebaudiana (Asteraceae)	Leaves (dried)	Used as antiproliferative/antimutagenic/antioxidant and natural sweetener	Flavonoids	Stevioside and proline	Salinity increases	Increase	Zeng et al. (2013)
Foeniculum vulgare Mill. (Apiaceae)	Seed	Used as diaphoretic, diuretic, carminative, expectorant, febrifuge, stomachic, stimulant, appetizer, cardiac stimulant, and vermifuge	Phenols, monoterpenoid glycosides	Furocoumarins imperatorin, psoralen, bergapten, xanthotoxin, isopimpinellin, quercetin, and kaempferol	Salinity increases	SMs concentration decreased	Nassar et al. (2010); Nourimand et al. (2012)
Plantago ovate (Plantaginaceae)	Root and shoot	Used as a emollient, demulcent, and a laxative	Flavonoids	Flavonoids saponins and proline	Salinity increases	Increase	Haghighi et al. (2012)
Capsicum sp. (*Solanaceae*)	Fruit	Used for rheumatoid arthritis, osteoarthritis, and other painful conditions	Phenolic compound	Capsaicin	Salinity increases	Increase	Arrowsmith et al. (2012)
Artemisia annua L. (Asteraceae)	Leaves	Used as antimalarial, anti-inflammatory, and anticancer	Tarpenoids and flavonoids	Artemisinin, arteanuin, artemether, arteether, artemetin, casticin, chrysoplenetin, and cirsilineol	Less salinity	SMs concentration increased	Weathers and Towler (2012); Aftab et al. (2010)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Salinity	Concentration variation	Key references
Origanum vulgare (Lamiaceae)	Leaves	Used as antiseptic, antispasmodic, carminative, cholagogue, diaphoretic, emmenagogue, expectorant, stimulant, and stomachic	Essential oil	Carvacrol, p-cymene, and γ-terpinene	Salt stress	Decreases	Said-Al Ahl and Hussein (2010)
Satureja hortensis (Lamiaceae)	Aerial parts	Used as antirheumatic, antiseptic, aromatic, carminative, digestive, expectorant, stings, and stomachic	Phenolic compound Terpinene	Carvacrol α-terpinene	Salt concentration increases Salt concentration increases	Increases Decreases	Najafi and Khavari-Nejad (2010)
Lycopersicon esculentum (*Solanaceae*)	Leaf	Used as first-aid treatment for burns/scalds and sunburn	–	Sorbitol and jasmonic acid	Salinity increases	Decreases	Tari et al. (2010)
Origanum majorana (Lamiaceae)	Shoots	Used for digestive problems like nausea, bloating, loss of appetite, intestinal spasm, diarrhea, and flatulence	Monoterpenes/ essential oils	(i) Oil contents (ii) *Trans*-sabinene Hydrate and γ-Terpinene (iii) *cis*-Sabinene Hydrate and linalyl acetate	(i) Salinity increases (ii) Salinity increases (iii) Salinity increases	(i) Decreases (ii) Decreases (iii) Increase	Baatour et al. (2010)
Mentha pulegium (Lamiaceae)	Aerial parts	Used as antiseptic, antispasmodic, carminative, diaphoretic, emmenagogue, sedative, and stimulant	Phenolic acid	Caffeic acid and rosmarinic acid	Salt stress	Increases	Queslati et al. (2010)

(continued)

Table 19.4 (continued)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Salinity	Concentration variation	Key references
Achillea fragratissima (Compositae)	Whole plant	Used for treatment of wounds, bleedings, headache, inflammation, pains, spasmodic diseases, flatulence, and dyspepsia	Phenolics alkaloid	Tannin	Salinity increases	Increase	Abd EL-Azim and Ahmed (2009)
Ricinus communis (Euphorbiaceae)	Shoot	Used for abdominal disorders, arthritis, backache, muscle aches, bilharziasis, chronic backache and sciatica, chronic headache, constipation, expulsion of placenta, gallbladder pain, period pain, menstrual cramps, rheumatism, sleeplessness, and insomnia	Alkaloids	Recinine alkaloids	Salinity increases	Increase	Ali et al. (2008)
Coriandrum sativum (Apiaceae)	Leaf	Used as an analgesic, carminative, digestive, antirheumatic, and antispasmodic agent	Monoterpenes/ essential oils	(i) Oil contents (ii) Octanal, Borneol and (*E*)-2-Nonenal (iii) α-Pinene and (*Z*)-Myroxide	(i) High salinity (ii) Salinity increases (iii) Salinity increases	(i) Decreases (ii) Increase (iii) Decreases	Neffati and Marzouk (2008)
Matricaria recutita Asteraceae	Flower	Use against gastrointestinal problems; and to treat irritation of the skin	Essential oil	α-bisabolol oxide	Salt stress	Increases	Baghalian et al. (2008)
Solanum nigrum L. (Solanaceae)	Fruits, leaves, roots	Used in chronic enlargement of liver, cough, skin disease, rheumatism, gout, and eye diseases	Steroidal alkaloid	Solasodine	Salinity increased	SMs concentration increased	Bhat et al. (2008)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Salinity	Concentration variation	Key references
Aloysia citrodora (Verbenaceae)	Shoot	Used as digestive disorders such as flatulence, indigestion, and acidity	Essential oil	Geranial and neral	Salinity increases	Decreases	Tabatabaie and Nazari (2007)
Trachyspermum ammi (Apiaceae)	Whole plant	Used as atonic dyspepsia, diarrhea, abdominal tumors, abdominal pains, piles, and bronchial problems, asthma, antispasmodic, and carminative	Essential oil	Cadinene, longifolene, thymol, and carvacrol	Salt stress	Decreases	Ashraf and Orooj (2006)
Matricaria chamomilla (Asteraceae)	Leaves	Used as spasmolytic, anti-inflammatory, and antibiotic	Flavonoids	Herniarin and umbelliferone	Salinity increased	SMs concentration decreased by 40%	Eliasova et al. (2004)

Table 19.5 Medicinal plants and their response under different light intensity

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Light	Concentration variation	Key references
Mahonia breviracema (Berberidaceae)	Root and shoot	Used as diuretic and demulcent	Alkaloids	Alkaloids	Full sunlight	Increases	Li et al. (2018)
Mahonia breviracema (Berberidaceae)	Leaf	Used as diuretic and demulcent	–	Essential oil	Full sunlight	Increases	Li et al. (2018)
Mahonia bodinieri (Berberidaceae)	Leaf	Used orally in the treatment enteric infections, especially bacterial dysentery	Hexadecanoic acid		50% sunlight	Increases	Li et al. (2018)
Mahonia bodinieri (Berberidaceae)	Whole plant	Used orally in the treatment enteric infections, especially bacterial dysentery	Alkaloids	Alkaloids	30% and 50% sunlight	Increases	Kong et al. (2016)
Flourensia cernua (Asteraceae)	Leaf	Used to gastrointestinal conditions and respiratory disorders	Alkaloids	Sabinene, β-pinene, borneol, bornyl acetate, and Z-jasmone	50% shade	Increases	Estell et al. (2016)
Erigeron breviscapus (Asteraceae)	Leaf	Used for cardiovascular disease, cerebral blockages and hemorrhage, and digestive disorders	Phenols	Scutellarin	Full sunlight	Increases	Zhou et al. (2016)
Pinus contorta (Pinaceae)	Seedling	Used as antiseptic, diuretic, rubefacient, vermifuge and vulnerary and for treatment of kidney and bladder diseases and rheumatic affections	Phenols	Pelargonidin	Short day of light	Increases	Camm et al. (1993)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Light	Concentration variation	Key references
Ipomoea batatas (Convolvulaceae)	Leaves	Used for the treatment of diabetes, hypertension, dysentery, constipation, fatigue, arthritis, rheumatoid diseases, hydrocephaly, meningitis, kidney ailments	Phenols	Catechins	Long day of light	Increases	Carvalho et al. (2010)
Ipomoea batatas (Convolvulaceae)	Leaves	Used for the treatment of diabetes, hypertension, dysentery, constipation, fatigue, arthritis, rheumatoid diseases, hydrocephaly, meningitis, kidney ailments	Phenols	Hydroxybenzoic acid	Long day of light	Increases	Carvalho et al. (2010)
Vaccinium myrtillus (Ericaceae)	–	Used for treatment of gastrointestinal tract disorders and diabetes, cardiovascular conditions, diabetes, as vision aids, diarrhea	Phenols	Chlorogenic acid	Long day of light	Increases	Uleberg et al. (2012)
Cyanea acuminate (Campanulaceae)	Leaves	Used for treatments for psoriasis, liver and stomach ailments, and common colds, leukemia	Alkaloids	Camptothecin	27% Sunlight	Increases	Liu et al. (1997)
Cyanea acuminate (Campanulaceae)	Roots	Used for treatments for psoriasis, liver and stomach ailments, and common colds, leukemia	Alkaloids	Camptothecin	27% Sunlight	Decreases	Liu et al. (1997)
Centella asiatica (Apiaceae)	Leaves	Used to repair nervous tissue due to spinal injury, neuromuscular disorders, and to increase general brain function and memory	Phenols	Asiatic acid	70% Shade	Increases	Devkota et al. (2010)
Centella asiatica (Apiaceae)	Leaves	Used to repair nervous tissue due to spinal injury, neuromuscular disorders, and to increase general brain function and memory	Phenols	Asiaticoside	Full sunlight	Increases	Devkota et al. (2010)

cadmium, the concentration of chlorogenic acid increases in *Vaccinium corymbosum* plantlets, while Sá et al. (2015) reported in their study that the production of carvone (essential oils) in *Mentha crispa* gets stimulated in the presence of lead. De and De (2011) investigated the impact of the treatment of chromium, nickel, cadmium, and copper on *Trigonella foenum-graecum* and found that the production of steroids, that is, diosgenin, gets inhibited by chromium and nickel, whereas cadmium and copper stimulated its production. Effect of chromium on the concentration of secondary metabolites of *Phyllanthus amarus* was studied by Rai and Mehrotra (2008). They have concluded that the concentration of phyllanthin and hypophyllanthin increases under chromium exposure. Sinha and Saxena (2006) found that in the presence of iron, the production of bacoside-A in roots and leaves of *Bacopa monnieri* increases, whereas the production of cysteine in roots increases and there is no effect in the production of cysteine in leaves. Similarly, in the presence of cadmium, there is no effect on the concentration of umbelliferone in *Matricaria chamomilla* (Kováčik et al. 2006). Narula et al. (2005) studied the plant culture of *Dioscorea bulbifera* and found that in the presence of copper, the production of diosgenin increases. The production of Eugenol (in the whole plant) and proline (in leaves) of *Ocimum tenuiflorum* increases in the presence of chromium (Rai et al. 2004). Murch et al. (2003) reported that the production of pseudohypericin and hypericin decreases in the presence of nickel in *Hypericum perforatum*, whereas the production of hyperforin gets completely inhibited under similar conditions. Further details associated with medicinal plants and their response to heavy metals are given in Table 19.6.

4 Conclusion

Human beings depend on plants for fulfilling their various needs. Medicinal/herbal plants are a good source of secondary metabolites used in pharmaceutical industries for drug synthesis and formulation. Concentration and content of secondary metabolites depend (increase/decrease) on harvest time, seasons, soil type, nutrient supply, altitude, geographical location, stage of plant (juvenile/mature), and genotypes or cultivars. Their production is under biotic (by the attack of herbivores, pets, and pathogens) and abiotic (such as temperature variation, drought, salinity, light intensity, and heavy metals) stresses. Secondary metabolites have a significant role in the tolerance and adaptation of plants to adverse environmental conditions. However, their synthesis mechanism is not fully examined, and further investigation is required to obtain the maximum production of secondary metabolites from important medicinal plants under normal as well as adverse environmental conditions.

Table 19.6 Medicinal plants and their response under heavy metals stress

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Heavy metals	Concentration variation	Key references
Vaccinium corymbosum (Ericaceae)	Plantlet	For treatment of wounds, skin diseases, and used to reduce pimples	Phenolic compound	Chlorogenic acid	Presence of cadmium	Increases	Manquian-Cerda et al. (2016)
Mentha crispa (Lamiaceae)	Leaves	Used for digestive disorders including gas, indigestion, nausea, diarrhea, upper gastrointestinal tract spasms, irritable bowel syndrome, bile duct and gallbladder swelling (inflammation), and gallstones	Essential oils	Carvone	Presence of lead	Increases	Sá et al. (2015)
Trigonella foenum-graecum (Fabaceae)	Whole plant	Used as antibacterial, a gastric stimulant, an antidiabetic, and a galactagogue and to combat anorexia	Steroids	Diosgenin	Presence of cadmium and copper	Increases	De and De (2011)
Trigonella foenum-graecum (Fabaceae)	Whole plant	Used as antibacterial, a gastric stimulant, an antidiabetic, and a galactagogue, and to combat anorexia	Steroids	Diosgenin	Presence of chromium and nickel	Inhibits the production	De and De (2011)
Phyllanthus amarus (Phyllanthaceae)	Whole plant	Used in the problems of stomach, genitourinary system, liver, kidney, and spleen	–	Phyllanthin, Hypophyllanthin	Presence of chromium	Increases	Rai and Mehrotra (2008)
Bacopa monnieri (Plantaginaceae)	Root and leaves	Contains powerful antioxidants, reduce inflammation, blood pressure, attention deficit hyperactivity disorder symptoms, anxiety and stress, and boost brain function	Saponins	Bacoside-A	Presence of iron	Increases	Sinha and Saxena (2006)

(continued)

Table 19.6 (continued)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Heavy metals	Concentration variation	Key references
Bacopa monnieri (Plantaginaceae)	Roots	Contains powerful antioxidants, reduce inflammation, blood pressure, attention-deficit hyperactivity disorder symptoms, anxiety and stress, and boost brain function	–	Cysteine	Presence of iron	Increases	Sinha and Saxena (2006)
Bacopa monnieri (Plantaginaceae)	Leaves	Contains powerful antioxidants, reduce inflammation, blood pressure, attention deficit hyperactivity disorder symptoms, anxiety and stress, and boost brain function	–	Cysteine	Presence of iron	No effect	Sinha and Saxena (2006)
Matricaria chamomilla (Asteraceae)	Whole plant	For treatment of sore stomach, skin care, irritable bowel syndrome, and as a gentle sleep aid	Phenylpropanoids	Umbelliferone	Presence of cadmium	No effect	Kováčik et al. (2006)
Dioscorea bulbifera (Dioscoreaceae)	Plant culture	For the treatment of piles, dysentery, syphilis, ulcers, cough, leprosy, diabetes, asthma, and cancer	Steroids	Diosgenin	Presence of copper	Increases	Narula et al. (2005)
Phyllanthus amarus (Phyllanthaceae)	Whole plant	Used in the problems of stomach, genitourinary system, liver, kidney, and spleen	–	Phyllanthin, hypophyllanthin	Cadmium stress	Increases	Rai et al. (2005)
Ocimum tenuiflorum (Lamiaceae)	Leaves	For the treatment of bronchitis, malaria, diarrhea, dysentery, skin disease, arthritis, eye diseases, and insect bites	–	Proline	Chromium treated	Increases	Rai et al. (2004)

Medicinal plant (family)	Plant part	Medicinal uses	Major class of secondary metabolite	Name of metabolite	Heavy metals	Concentration variation	Key references
Ocimum tenuiflorum (Lamiaceae)	Whole plant	For the treatment of bronchitis, malaria, diarrhea, dysentery, skin disease, arthritis, eye diseases, and insect bites	Phenol	Eugenol	Chromium stress	Increases	Rai et al. (2004)
Hypericum perforatum (Hypericaceae)	Whole plant	For the treatment of several disorders, such as minor burns, anxiety, and mild-to-moderate depression	Terpenes	Hyperforin	Presence of nickel	Inhibits the production	Murch et al. (2003)
Hypericum perforatum (Hypericaceae)	Whole plant	For the treatment of several disorders, such as minor burns, anxiety, and mild-to-moderate depression	Terpenes	Pseudohypericin, hypericin	Presence of nickel	Decreases	Murch et al. (2003)

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