Medicinal Plants and Abiotic Stress: An Overview

Shakeelur Rahman, Muhammad Iqbal, and Azamal Husen

Abstract Medicinal plants, like others, are affected by biotic as well as abiotic stress. The latter category includes a variety of stressors such as drought, flooding, salinity, temperature extremes (hot as well as cold), UV radiations, gaseous pollutants, heavy metals & metalloids, nutrient deficiency, and pesticides, among others. Low doses of these stresses stimulate metabolic activities in plants but higher doses negatively affect the overall plant performance by limiting the genetic potential, growth, photosynthesis, metabolic capacity and yield. These stresses also produce free radicals, such as superoxide and peroxide ions, which is a source of injury to the various plant systems. Almost all abiotic stresses damage the photosynthetic device at various levels of its organization such as chloroplast ultrastructure, and the pigments, lipids and protein composition. Production and relative distribution of photosynthate influence the growth and development, morpho-anatomical traits, and secondary metabolites (SMs) biosynthesis in the affected plants. Variation in the quality and concentration of SMs means a lot in medicinal plants, because the therapeutic efficacy of these plants is in fact dependent on these metabolites. However, most of the plants defy the adverse effect of the stressors by means of adequate defense mechanisms and tolerance potential through integrated cellular and molecular reactions. This chapter reviews the overall impact of abiotic stresses on growth features, developmental processes, cytological and physiological parameters, and SMs production in medicinal plants.

Keywords Abiotic stress · Climate change · Growth performance · Medicinal plants · Secondary metabolites

S. Rahman
Prakriti Bachao Foundation, Ranchi, Jharkhand, India

M. Iqbal
Department of Botany, School of Chemical and Life Sciences, Jamia Hamdard, New Delhi, India

A. Husen (✉)
Wolaita Sodo University, Wolaita, Ethiopia

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1 Introduction

Phytodiversity, encompassing the medicinal plants, plays a key role in the nutrition, health and livelihood of humans and animals. Man has been trying from times immemorial to benefit from plants for fighting against diseases and physical disorders (Anis et al. 2000; Atique et al. 1985a, b, 1986). Today, he is keen on improving their productivity and efficacy using different nutritional, genetical, agricultural and phytochemical techniques (Iqbal and Ahmad 2014; Aftab and Hakeem 2020; Beshah et al. 2020; Sharma et al. 2020; Husen et al. 2021; Husen 2022a; Asfaw et al. 2022). However, consequent upon rapid industrialization and construction works in the recent past, changes in climatic condition and ever-increasing environmental pollution have caused a direct threat to various plant species, including those of medicinal importance (Ahmad et al. 2011; Husen 2021a, 2022b). Over the coming decades, degradation of medicinal plants' diversity is likely to be faster due to climate changes. Plants are highly sensitive; they tend to resist the stress and do not generally adapt rapidly to the changed environment (Iqbal et al. 1996, 2018; Pimm 2009). Thus, the climate change may have an indirect effect on the traditional healing systems that are based primarily on medicinal plants and herbal drugs (Arya et al. 2022, Beigh et al. 2002b; Parveen et al. 2020a, b, 2022; Rahman and Husen 2021, Husen 2022a, b, c). Medicinal plants exposed to hostile environmental conditions. For instance, light stress, low or high temperature, ultraviolet (UV) radiation, salinity, drought, air pollutants, nutrient deficiency and heavy metals stress results normally in stunted plant growth, altered metabolite production, emission of hydrogen peroxide, superoxide and hydroxyl radicals, and activation of defence mechanisms (Iqbal et al. 2011a, b; Qureshi et al. 2011; Wani et al. 2016; Husen 2021b, c).

The unfavorable environmental conditions have tremendous impacts on medicinal plants at cellular, molecular and the overall physiological levels. Futther, the global rise of temperature due to climate change has to give rise to visible impacts on life cycles and the pattern of distribution of various species of medicinal and aromatic plants. Additionally, the raised level of gases, like ozone, and oxides of carbon, sulphur and nitrogen in the atmosphere, is also inflencing the quality and productivity of medicinal plants species, causing changes in their active ingredients (Idso et al. 2000; Iqbal et al. 2018; Deepti et al. 2022a; Rahman and Husen 2022).

The medicinal and aromatic plants control biosynthesis of their secondary metabolites (SMs) to be able to survive under various biotic and abiotic stress situations. These plants use different mechanisms to deal with the stressful situations. Their responses depend on types of stress, duration of stress, and plant species. They synthesize a variety of SMs with varied chemical composition, from primary metabolites, viz. amino acid, carbohydrates, and lipids. These metabolites, which are involved in the defense of plants against environmental stresses, pathogens and herbivores, are also beneficial to humans due to their pharmaceutical, nutritive and cosmetic value (Seigler 1998; Bachheti et al. 2021; Husen and Iqbal 2021). Taken together, this chapter reports the influence of abiotic stress on growth and

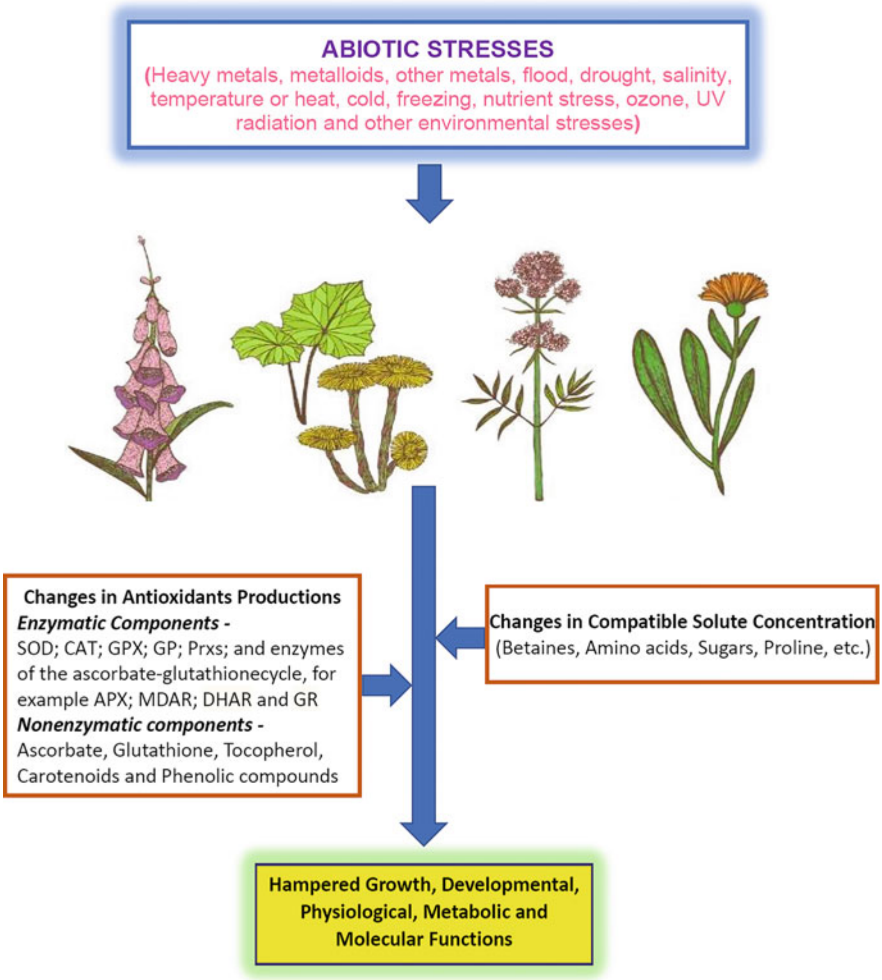

Fig. 1 Effect of abiotic stress on medicinal plants (where SOD, CAT, GPX, GP, Prxs; APX, MDAR, DHAR, and GR stand for superoxide dismutase, catalase, glutathione peroxidase, guaiacol peroxidase, peroxiredoxins, ascorbate peroxidase, monodehydroascorbate reductase, dehydroascorbate reductase and glutathione reductase, respectively)

development, cytological, biochemical and physiological mechanisms and production of SMs in medicinal and aromatic plants. The overall impact of abiotic stresses on these plants is presented in Fig. 1.

2 Abiotic Stresses and Medicinal Plants

2.1 Temperature Stress

Temperature is a main abiotic factor that decides the level of photosynthesis, and hence of plant growth, and other physiological processes. Not only that the growth parameters in the primary plant body are affected by environmental temperature, but even the secondary growth cycle in woody plants is regulated by changes in temperature (Ajmal and Iqbal 1987; Fahn and Werker 1990; Iqbal and Ghouse 1980, 1985; Iqbal 1994, 1995), and the structural pattens of the secondary tissues are determined largely by the thermal condition of the habitat, as is evident, for instance, from the ring-porous and diffuse-porous texture of wood (Ghouse and Iqbal 1982; Ajmal and Iqbal 1988; Gizińska et al. 2015). Cold, chilling, frost and heat come under the temperature stress. Several reports have scrutinized the impacts of enhanced temperatures on the production of plant secondary metabolites. Temperature affects the plant ontology and metabolic activity, and brings premature leaf senescence (Peerzada and Iqbal 2021). Thermal treatments influenced the contents of carotenoids, including β-carotene, in Brassicaceae, and the concentration of steroidal furostanol and spirostanol saponins increased due to low soil temperatures (Szakiel et al. 2011). Fluctuations in temperature have a manifold influence on plant growth, metabolic regulation, rate of intracellular reactions and permeability in plant cell cultures (Morison and Lawlor 1999). Leaf senescence and concentrations of root SM were increased by elevated temperatures in *Panax quinquefolius*. An increase in temperature (by 5 °C) decreased the rate of photosynthesis and production of biomass significantly (Jochum et al. 2007). The temperature and light-quality effects on the production of ginsenoside in hairy root culture of *Panax ginseng* were observed by Yu et al. (2005). Increased temperature changed the timing of crop flowering and seed development, which are critical developmental phases in the life cycle of majority of medicinal plants. Jagadish et al. (2008) have shown that the temperature levels (>32–36 °C) significantly decrease the seed set and crop yield. Reports have shown that various plants are at a high risk due to high temperature and strong heat waves with respect to their growth and development, and have to devise various adaptive strategies (Cleland et al. 2012; Bhatla and Tripathi 2014; Noor et al. 2019). High temperature hampers the vegetative growth, metabolite production and yield of medicinal plants (Hatfield and Prueger 2015).

Plants can observe even 1 °C increase and or decrease in temperature due to their natural sophisticated mechanism (Kumar and Wigge 2010). Mittler et al. (2012) have suggested that there are a number of pathways, regulatory networks and cellular components engaged in the defence of plant system against heat stress. Bita and Gerats (2013) have also reported that the levels of several hormones like ethylene, ABA and salicylic acid (SA) are enhanced due to heat stress, as they control the unfavorable impacts of abiotic stress situations in plants. SA regulates important plant physiological activities like proline metabolism, nitrogen metabolism, antioxidant defense system, photosynthesis, and plant-water relations under abiotic stresses (Khan et al. 2015). Further, the kinds of thermotolerance decide the requirement for different hormones and their response to signaling. Plant tolerance to heat stress improves the SA content in *Ocimum basilicum* (Clarke et al. 2004). Hasanuzzaman et al. (2013) have reported that the heat stress hinders the rate of photosynthesis due to decrease of soluble proteins and Rubisco-binding proteins. Heat enforces harmful effects on leaves (e.g., decreased leaf area, leaf water potential and pre-mature leaf senescence), which cause adverse impacts on the rate of photosynthesis (Peerzada and Iqbal 2021). Decreased activities of ADP-glucose pyrophosphorylase, invertase and sucrose phosphate synthase also influenced the synthesis of starch and sucrose (Rodríguez et al. 2005).

Heat stress also affects sexual reproduction and flowering processes because high temperature is fatal to the flowering stage and bud initiation, thus decreasing the productivity of crop plants ultimately (Thakur et al. 2010). Perhaps, this is due to a decreased water and nutrient transport during reproductive phase. Heat stress causes the down-regulation of sucrose synthase and a number of cell wall and vacuolar invertases in the developing pollen grains. It disrupts the sucrose and starch yield and reduces the soluble carbohydrates deposition (Sato et al. 2006).

Alterations in physiological features and metabolic perfomances in *Portulaca oleracea* due to heat, drought and combined stresses include a higher malondialdehyde level, peroxidase and superoxide dismutase activities, amino acid asparagine content and electrolyte leakage (Jin et al. 2015). On the contrary, chlorophyll content declined. Glycine betaine plays a vital role in plants exposed to high temperatures (Sakamoto and Murata 2002). The deposition of anthocyanin due to heat stress decreases the osmotic potential of the leaf, which in turns accelerates the uptake of water and decreases the rate of transpiration. Zhong and Yoshida (1993) have noticed a significant decrease in anthocycnins concentrations in *Perilla frutescens* suspension cultures, when temperature was augmented to 28 ° C, whereas the pigment productivity was optimal at 25 ° C. Release of the anthocyanin pigment due to distinct temperatures was reported from hairy root cultures of *Beta vulgaris* (Thimmaraju et al. 2003). Meiri et al. (2010) have shown that *Arabidopsis* overexpress the chyB gene that codes for β-carotene hydroxylase, which participated in the biosynthetic pathway of zeaxanthin. Zeaxanthin causes tolerance to augmented temperature and prevents membranes from oxidative damage (Meiri et al. 2010).

Temperature has immense impact on SM production in plants (Ramakrishna and Ravishankar 2011). Reda and Mandoura (2011) have reported that high-temperature stress reduces chlorophyll biosynthesis in plastids. Plant metabolism creates heat-stress tolerance by producing energy and the SMs, which is essential for cellular homeostasis. Saponins found in *Panax ginseng* leaves, stems, bulbs, flowers, fruit and roots get affected by different abiotic factors (Szakiel et al. 2011). Lin et al. (2009) have suggested that the upsurge of saponins in reproductive organs plays a role in chemical protection of plants in the adverse environmental situations. The American ginseng has a higher root ginsenoside content in plants exposed to long-period sunlight than in those exposed to shorter duration of direct sunlight (Li et al. 1996).

Beigh et al. (2002a) studied the effect of various treatments, including the hot water treatment and chilling for different durations (15–120 days), on *Aconitum heterophyllum* seed germination and seedling survival. The percentage of seed germination and the seedling-survival rate were appreciably enhanced by all treatments under laboratory as well as field conditions, but pre-chilling was most effective. Low temperature brings morphological and structural variations in medicinal plants, altering the membrane fluidity and the cell osmotic potential, and triggering changes in the macromolecules' activity. Photosynthetic apparatus exhibits CO_2 assimilation inhibition, and photoinhibition of photosystem I (PSI), PSII and diverse enzymatic activities due to cold stress. Also, there occurs a rise in the ROS production that stimulates damage to membranes, lipids, proteins, DNA and RNA (Sevillano et al. 2009).

Plant metabolism in temperate regions is redirected for synthesis of cryoprotectant molecules such as sugar alcohols, soluble sugars and nitrogenous compounds (low-molecular weight) in excessive winters (Janska et al. 2010). Phenolic production is increased due to cold stress. The lignin and suberin depositions increase resistance to cold temperatures, thus protecting plants from freeze damage (Griffith and Yaish 2004). Anthocyanins are also deposited during cold stress (Christie et al. 1994). In *Pinus pinaster*, the water and cold stresses produce changes in endogenous jasmonates (Pedranzani et al. 2003). Zhao et al. (2011) suggested that melatonin ensures the survival of cryopreserved *Rhodiola crenulata* callus. Cold stress directly affects the SMs of *Ocimum tenuiflorum*, thus reducing the eugenol content (Rastogi et al. 2019). Plant growth in *Datura stramonium* was affected due to temperature stress. However, increase in the enzymatic and non-enzymatic antioxidants indicates that the plant can control the level of cellular reactive oxygen species (ROS) and grow effectively under stressful conditions. At high and low temperatures, alkaloidal content of *D. stramonium* increases the tolerance ability with strong antioxidant defense mechanism (Shriya et al. 2019). The temperature and water stresses inhibit vegetative growth of *Ocimum basilicum* and cause proline deposition in leaves, which works as an osmolyte for osmotic adjustment in the stressful conditions. Glycine betaine also accumulates against the exposure of temperature and water stress in basil plants. The other metabolites, namely carotenoids or total soluble sugars, decline in *O. basilicum* leaves against the stress (Al-Huqail et al. 2020). The stimulation of SMs due to heat stress could perform as a noticeable mechanism of cross-protection against stresses (Arbona et al. 2013).

Viability of seeds in tropical plants is known to be negatively influenced by chilling temperatures. The stored seeds of Neem (*Azadirachta indica*) are sensitive to chilling when their moisture content is $\geq$10%. This limits the possibility of their preservation for long duration (Tompsett 1994). *Zingiber officinale* exposed to chilling stress may characteristically exhibit structural damages and undergo to decomposition of metabolic compounds. Chilling stress may inhibit enzymatic and photochemical activities and generate reactive oxygen, like hydroxyl radicals, hydrogen peroxide and superoxide, causing severe oxidative damage (Li et al. 2014).

Composition of lipid is a major factor in membrane stabilizations, hence plays the main role in developing the stress tolerance (Anjum et al. 2015). Unsaturated fatty acids are related with the cold tolerance, as these are found in greater amount in plastid membrane of the cold-resistant than of the cold-sensitive plants. Plant membranes experience transition from a liquid crystalline to a gel-like phase with a reduced fluidity (at low temperatures); this is accompanied with leakage of ions and membrane-integrated proteins deactivation (Upchurch 2008). Some of the medicinal plants like *Cistus incanus, Phlomis fruticose, Satureja thymbra, Teucrium polium* and *Thymus sibthorpii* exhibit seasonal dimorphism (Lianopoulou and Bosabalidis 2014) by evolving mechanical and chemical defensive obstacles to manage the stress under cold conditions. These plants develop structural, physiological, and biochemical defense mechanisms, and these changes are quite often facilitated by phytohormones.

Lianopoulou and Bosabalidis (2014) have reported that *Origanum dictamnus* induced structural and functional variations under cold conditions, affecting the shape, size and distribution of leaves. Mesophyll cells developed large intracellular spaces for ample air deposition. *O. dictamnus* also accelarates the development of a thick and dense layer of non-glandular trichomes as a defensive armor, together with a thick cuticle layer on the leaf epidermis under stress. Essential oils are more profusely released by glandular hairs under cold stress, p-Cymene (60%) being the most important constituent during the winter while carvacrol (42%) during the summer.

Salvia sclarea, an important medicinal herb, exhibited a decrease in leaf area but an increase in spikes' length and number, and a longer inflorescence with more essential oils in cold stress situations (Kaur et al. 2015). *Teucrium polium* and *Thymus sibthorpii* are also influenced due to chilling, as leaves are smaller and thicker and have a higher number of stomata and glandular hairs, whereas mesophyll and epidermal cells contain dark phenolic and calcium oxalate crystals in their vacuoles in winter season (Lianopoulou et al. 2014a, b).

Phytohormones regulate all growth features; generally, ABA is responsible for stomatal closure, thus slowing down the rate of photosynthesis, as seen in leaves of *O. dictamnus* in winter season (Lianopoulou and Bosabalidis 2014). However, an elevated rate of photosynthesis and stomatal conductance was observed in winter leaves of *Thymus sibthorpii* and *Teucrium polium* (Lianopoulou et al. 2014a, b), indicating that the physiological changes also vary with plant species.

It has been observed that certain abiotic stress situations are associated with a higher deposition of antioxidant compounds in various medicinal plants (Qureshi et al. 2013; Saema et al. 2016), and often increase the medicinal or nutritional value of those plants (Saba et al. 1999; Mir et al. 2015). Production of biomass, chlorophyll and β-carotene content and also the antioxidant activity enhanced in response to cold stress in the growing seedlings of *Foeniculum vulgare* (Nourimand et al. 2012). The leaves of Indian ginseng demonstrated an upsurge in the deposition of withanolide, a key bioactive compound, in response to cold stress. However, cold stress slightly reduced the withanolide concentration in root tissues (Kumar et al. 2012; Mir et al. 2015), indicating that various plants and their parts have evolved a specific kind of mechanisms against cold stress. Cold is also related to rise in antioxidant enzymatic activity, as noticed in the leaves of Indian ginseng (Mir et al. 2015) and *Thymus sibthorpii* (Lianopoulou et al. 2014b). This provides protection to the aerial tissues of plants from cold-caused damage. The transfer of WsSGTL1 gene in *Arabidopsis thaliana* resulted in increased tolerance against cold and a quicker formation of sterol glycosides coupled with a higher enzymatic activity in transgenic plants (Mishra et al. 2013). In addition, the gene overexpression improved tolerance to cold stress together with an elevated stomatal conductance, a better photosynthetic performance and regulation of PSI and PSII (Saema et al. 2016).

Serotonin is an indoleamine neurohormone in vertebrate animals. It is also found in several plants, and helps in different physiological functions such as protection against pathogenic infection and environmental stress. It has a defensive role against ROS, causing suspension in senescence (Ramakrishna et al. 2011a, b). According to Murch et al. (2009), serotonin works as an antioxidant to protect the young reproductive tissues from harsh environmental conditions in *Datura metal*. The cold stress exposure augmented the concentrations of serotonin in *D. metal* (Murch et al. 2009).

2.2 Drought Stress

Drought stress affects the plant development and growth processes; even the secondary growth phenomena, including the cambial periodicity and wood-formation pattern undergo alterations (Aref et al. 2014). Tolerance to drought stress is noticed in all plants, but its impact varies from one plant species to another. It occurs due to water shortage, often accompanied by high temperatures and solar radiation (Xu et al. 2010). Drought frequently causes oxidative stress and increases the antioxidant enzymes activity, non-enzymatic defence materials, flavonoids and phenolic acids (Larson 1988; Anjum et al. 2008; Aref et al. 2013a, b). It changes the chlorophyll a and b ratio, and carotenoids content (Anjum et al. 2003). A decline in chlorophyll content, photosynthesis and metabolite synthesis has been reported in several plants such as *Catharanthus roseus*, *Brassica carinata*, *Sorghum bicolor*, *Pisum sativum* and *Vicia faba* under drought stress (Osman et al. 2007; Getnet et al. 2015; Embiale et al. 2016; Husen et al. 2014, 2017). *Chenopodium quinoa* plants growing under low water-deficit condition showed that the saponin content decreased by 0.46% (dry weight) as against 0.38% under high water-deficit condition (Soliz-Guerrero et al. 2002). Anthocyanins (a class of water-soluble flavonoids present in all tissues of higher plants) are known to deposit in plant tissues under drought and cold temperatures (Chalker-Scott 1999). In fact, flavonoids provide protection to plants growing in soils contaminated with toxic metals (Winkel-Shirley 2001). The heat and drought stress severely affected the growth and metabolism of *Artemisia sieberialba* by decreasing water uptake and use efficiency. Differential expression of the heat and drought stress responsive genes reflects a sort of dual functioning under the collective effect of heat and drought stresses. Their interactive tolerance mechanism at the biochemical and molecular levels is not clear (Haifa and Alhaithloul 2019).

The impact of drought on the SMs of different medicinal plant species, such as glycosides of rosmarinic acid in *Salvia miltiorrhiza (*Liu et al. 2011) and *Scrophularia ningpoensis* (Wang et al. 2010); morphine alkaloids of *Papaver somniferum* (Szabo et al. 2003); chinolizidin alkaloids of *Lupinus angustifolius* (Christiansen et al. 1997); epicatechins of *Camellia sinensis* (Hernández et al. 2006); chlorogenic acid of *Helianthus annuus* (Del Moral 1972) and betulinic acid of *Hypericum Brasiliense* (Nacif de Abreu and Mazaferra 2005), have been recorded. Drought stress caused an upsurge in the monoterpene concentrations in *Salvia officinalis* (Nowak et al. 2010). Analogous research with *Petroselinum crispum* has discovered a drought-caused enrichment of monoterpenes concentration in leaves (Petropoulos et al. 2008). Likewise, phenolic compounds concentration was significantly improved in *Hypericum brasiliense*. Although the stressed *H. brasiliense* plants were relatively smaller in comparison to the well-watered controls, the biomass as well as the concentration of phenol was considerably more in the stressed plants due to increased phenolic compounds concentrations (de Abreu and Mazzafera 2005).

2.3 Salinity Stress

Salinity is responsible for cellular dehydration that leads to osmotic stress and elimination of water from the cytoplasm, thus, decreased cytosolic and vacuolar volumes are noticed. Salinity stress produces species of reactive oxygen and causes oxidative stress (Alharby et al. 2019a, b). It frequently creates ionic and osmotic stress in plants, leading to severe impacts on specific SMs (Ali et al. 1999a; Arshi et al. 2002, 2006a; Mahajan and Tuteja 2005). Salinity hinders the rate of photosynthesis and plant growth by disrupting the nutrient-uptake equilibrium maintained by the plant (Arshi et al. 2004). Availability, partitioning and transport of nutrients and photosynthate are often affected, resulting in functional as well as structural alterations (Ali et al. 1999b; Mahmooduzzafar et al. 2003). This is owing to the competition of Na^+ and Cl^- ions with the nutrient ions like K^+, Ca_2^+ and NO_3^-. Abundance of Na^+ and Cl^- ions disturbs the ionic balance which directly acts upon the biophysical and metabolic components of the plant (Banerjee et al. 2016). Higher Na^+ and Cl^- during salinity result in reduced levels of N, P, K^+, Ca^{2+} and Mg^{2+} in plants, like fennel, lemon, peppermint, *Achillea fragratissima, Matricaria recutita*, *Trachyspermum ammi*, and *Verbena* spp. (Queslati et al. 2010).

Seedling is considered to be the most susceptible stage in the plant's life cycle. Salinity was found to cause a remarkable decrease in *Thymus maroccanus* seedling growth by hindering reserve food mobilization, suspending cell division, enlarging and injuring hypocotyls. Comparable observations are also noticed for basil, chamomile and marjoram (Aziz et al. 2008; Said-Al Ahl and Omer 2011). Anthocyanins and polyphenol contents are reported to increase in a number of plants under salinity

(Parida and Das 2005). In contrast, anthocyanin level was found to decrease in the salt-sensitive species of potato (Daneshmand et al. 2010). The salt-tolerant alfalfa plants quickly doubled root proline content, however in salt-sensitive plants the increase was slow (Petrusa and Winicov 1997). Proline accumulation showed a correlation with salt tolerance in *Aegiceras corniculatum* (Aziz et al. 1998), whereas total phenolics content increased with a moderate saline stress in red peppers (Navarro et al. 2006). Plant polyamines seem to be involved in plant response to salt stress. Salt stress-induced changes of free and bound polyamine levels have been observed in the roots of *Helianthus annuus* (Mutlu and Bozcuk 2007). Salinity affects different SMs of medicinal plants such as sorbitol of *Lycopersicon esculentum* (Tari et al. 2010); GABA of *Sesamum indicum* (Bor et al. 2009); tropane alkaloids of *Datura innoxia (*Brachet and Cosson 1986) and polyphenol of *Cakile maritime* (Ksouri et al. 2007).

Salinity shows adverse effect on growth and development of plant parts including the length and dry weight of root and shoot of *Artemisia annua*. Photosynthetic parameters and total chlorophyll content are normally reduced under salinity stress (Hussein et al. 2017). It considerably increases the electrolyte leakage and proline content (Aftab et al. 2010). Proline and activity of antioxidant enzyme significantly increase under different salt stress concentrations and enhance the inhibitory effect on growth and photosynthetic features (Qureshi et al. 2013; Li et al. 2014; Yousuf et al. 2017). Similarly, salinity stress inhibits growth, development, biochemical properties and SM accumulation in *Mentha piperita*. Antioxidant enzyme activity, lipid peroxidation and proline content increase significantly, while essential oil content decreases as the salinity increases (Coba and Baydar 2016). Salinity resulted in reduced number of leaves, leaf area and leaf biomass in *Mentha piperita* var. *officinalis* and *Lipia citriodora* var. *verbena* (Tabatabaie and Nazari 2007). *Solanum nigrum* showed enhanced production of solasodine content, a steroidal alkaloid, when grown under salinity stress. Solasodine is used as progenitor for the commercial steroidal drug production (Bhat et al. 2008). Salt stress also induced disorder in the mineral nutrition and affects the growth, antioxidant properties, physiological activities and phenolic content of *Trigonella foenum-graecum* (Baatour et al. 2010). Reduction in foliage, root growth and dry matter was also observed in *Aloe vera* under salinity (at 2, 4, 6 and 8 ds m^{-1}) (Moghbeli et al. 2012). Similarly, higher concentration of salt levels decreased the number of tillers in *Citronella java* (Chauhan and Kumar 2014). Different salt concentrations inhibited the fresh and dry weights and reduced the chlorophyll *a* and *b*, and β-carotene contents of the *Foeniculum vulgare* seedlings (Nourimand et al. 2012).

Salt stress influences seed germination. For instance, reduced seed germination was recorded in *Eruca sativa*, *Ocimum basilicum*, *Petroselinum hortense* and *Thymus maroccanus*, when seeds were sown in the salt-contaminated soil (Miceli et al. 2003). Growth features were found to be suppressed under salt stress in *Achillea fragratissima*, *Bacopa monniera*, *Cassia angustifolia*, *Catharanthus roseus*, *Chamomilla recutita*, *Nigella sativa*, *Ocimum* spp., *Salvia officinalis*, *Thymus vulgaris* and *Withania somnifera* (Ali et al. 1999b; Arshi et al. 2004; Jaleel et al. 2008a, b; Hussain et al. 2009). Accelarated salinity unavoidably affected the overall productivity of certain medicinal plants, including fennel, cumin, milk thistle, *Ammi majus* and *Trachyspermum ammi*. The fruit yield and the number of umbels per plant significantly decreased in the stress-exposed *Trachyspermum ammi*, the ajwain plant (Ashraf and Orooj 2006).

Quite often, abiotic stress affects the photosynthetic features of plants. This physiological function is the most essential for plant growth performance and survival (Iqbal et al. 2000; Bashir et al. 2015; Husen 2021a, b). It has been reported by Said-Al Ahl and Omer (2011) that the chlorophyll *a* and *b*, and the total chlorophyll content, were decreased in several plants, such as *Centaurium erythraea, Satureja hortensis, Teucrium polium*, *Thymus vulgaris*, *Zataria multiflora* and *Ziziphora clinopodioides*. This reduction in the the content of various photosynthetic pigmants is mostly due to the chlorophyll synthesis inhibition together with an augmented chlorophyll degradation.

Under salinity stress, the oil yield was reduced in the *Ricinus communis* roots, but increased in shoots (Ali et al. 2008a). In *Coriandrum sativum* leaves, the total fatty acid content was considerably decreased due to exposure of salt stress condition. Increase in NaCl concentrations caused a significant decline in the unsaturated to saturated fatty acid ratio, which accelerated the formation of rigid membrane (Neffati and Marzouk 2009). However, Anitha and Ranjitha Kumari (2006) have reported increased concentration of reserpine in *Rauvolfia tetraphylla* under salt stress condition. In *Ricinus communis*, amount of ricinine alkaloids declined in roots under salt stress condition, though their amounts were higher in shoots (Ali et al. 2008a). A study of the root proteome from a culture of hairy roots of *Panax ginseng* indicated that a combination of internal sequencing and expressed sequence tag database analysis was a nice identification method for proteome analysis of plants having incomplete genome data like *P. ginseng*. Further, study also suggested that expression of certain proteins may be exclusive for different tissues according to the specific cellular functions (Kim et al. 2003). Differential modulation of spinach proteome was observed in response to salinity stress and cadmium stress applied singly as well as in combination (Bagheri et al. 2015; Qureshi et al. 2015). Yousuf et al. (2016b) observed a differential expression of 21 proteins in shoots of a salt-tolerant genotype and a salt-sensitive genotype of *Brassica juncea* (Indian mustard) grown under salt stress. These proteins were linked to various physiological functions. Likewise, analysis of expression of chloroplast proteins in these genotypes exposed to salt stress could enable identification of proteins related to a variety of chloroplast-associated molecular processes, including the oxygen-evolving process, PS I and PS II functioning, Calvin cycle, and redox homeostasis. Further, Yousuf et al. (2016a) confirmed the above reults using the expression analysis of genes encoding the differentially-expressed proteins through real time PCR. Deposition of phenolics with higher salt concentration was also noticed in *Mentha pulegium and Nigella sativa*. The biosynthesis of phenolic compounds like trans-cinnamic acid, quercetin and apigenin was enhanced in *Nigella* grown on a highly saline soil (Bourgou et al. 2010). Cardenolide is a steroid derivative present in some plants such as *Digitalis purpurea*. Extract of *D. purpurea* is used to treat cardiac failures. Cardenolides occur mostly in the form of glycosides containing structural groups derived from sugars. An elevated cardenolide level was recorded in *D. purpurea* roots and leaves under a moderate salt stress (Morales et al. 1993).

The economically valuable essential oils are especially present in mint species such as *Mentha piperita*, *M. pulegium* and *M. suaveolens*. Salnity reduced the yield of essential oils (monoterpenes) in all mint species, but the percentage of one essential oil (menthone) increased with the increase in salt concentration condition. Poorer yield of essential oils under saline condition was also observed in Basil, Fennel, *Trachyspermum ammi* and *Thymus maroccanus* (Ashraf and Orooj 2006). The salinity decreased even the anethole content in fennel (Abd El-Wahab 2006). Moreover, several essential oil compounds like a-bisabolonoxide A, a-bisabololoxide B, chamazulene, a-bisabolol oxide A, trans-b-farnesene and a-bisabolol were found to increase under saline condition (Baghalian et al. 2008). Effort has also been made to understand the impact of salinity stress on plants through the study of proteome (Hakeem et al. 2012, 2013). Intensity of the impact of NaCl may be alleviated by application of certain other ions such as calcium (Arshi et al. 2005, 2006b; Yousuf et al. 2015), potassium (Umar et al. 2008, 2010; Yousuf et al. 2015) and sulphur (Anjana et al. 2006; Saifullah et al. 2016) in addition to hormones, like indole acetic acid, SA and jasmonates (Husen et al. 2016, 2018, 2019; Siddiqi and Husen 2019).

2.4 Heavy Metal Stress

Different toxic heavy metals (HMs) such as chromium (Cr), nickel (Ni), arsenic (As), cadmium (Cd), mercury (Hg) and lead (Pb) are rigorously released in the environment from sources like fertilizers, pesticides, metal smelters and industrial effluent, and influence the plant health and performance (Qureshi et al. 2005; Gauba et al. 2007; Diwan et al. 2010a; Rasool et al. 2013). These HMs are present in the soil as metal complexes in soluble form, exchangeable metal ions, and insoluble oxides, free metal ions, hydroxides, carbonates, or ingredient of structural silicates (Rai et al. 2004; Umar et al. 2005; Ansari et al. 2012). They affect not only the physiological and biochemical characteristics but also the developmental and morphological aspects of plants (Mehindirata et al. 2000; Khudsar et al. 2001; Ahmad et al. 2005; Anjana et al. 2006). Medicinal plants grown in HM-polluted environment tend to change their SM profile through stimulation or suppression of the secondary bioactive compounds (Iqbal and Khudsar 2000). Exposure to HM is a source of generation of oxidative stress in plants, activating the formation of highly active signaling molecules that affect the SM production, which influences the medicinal potency of the plants concerned (Nasim and Dhir 2010).

Higher euginol as well as proline content in *Ocimum tenuiflorum* was found under chromium stress, although photosynthetic pigments, protein, cysteine, ascorbic acid and non-protein thiol contents were reduced. Besides, chromium also accelerated lipid peroxidation coupled with potassium leakage (Rai et al. 2004). Increased accumulation of chromium and cadmium on the leaves of *Phyllanthus* *amarus* enhanced the contents of phyllanthin and hypophyllanthin, which are therapeutically essential SMs of the plant (Rai and Mehrotra 2008; Rai et al. 2005). Zhou et al. (2016) reported that the cadmium treatment increased the biosynthesis of arteannuin B, artemisinin and artemisinic acid in *Artemisia annua*. Application of nickel to *Hypericum perforatum* reduced the production of pseudohypericin and hypericin; capability of the plant to synthesize hyperforin was not noticed (Murch and Saxena 2002). Cao et al. (2009) reported that the accumulation and uptake of arsenic in *Sculellaria baicalensis* inhibit the formaton of baicalin and wogoninside, but the generation of baicalein, wogonin and oroxylin A was increased.

The elevated concentrations of trace metal nickle hamper plant growth (Hagemeyer 1999), and decrease the anthocyanin levels (Hawrylak et al. 2007). Co^{2+} and Cu^{2+} cause stimulatory effect on the SMs production. Cu^{2+} accelerated the betalains production in *Beta vulgaris* (Trejo-Tapia et al. 2001). However, Obrenovic (1990) observed stimulatory effects of Cu^{2+} on betacyanins accumulation in *Amaranthus caudatus* callus cultures. Under Cd^{2+} or Cu^{2+} exposure, sunflower leaf disks showed a remarkable decrease in spermidine content but no variation in spermine level was noticed (Groppa et al. 2001).

Chemical wastes, including those containing nanoparticles (NPs), are released from the household and the industrial and medical products, and accumulate in two major environmental sinks, *viz.* soil and water. As the plants are stationary with these natural substrata (soil and water), they cannot get away from the severe effects of the chemical pollutants present therein. Nanoparticles have been found to stimulate the generation of ROS and must therefore affect the secondary metabolism of plants (Marslin et al. 2017). However, some NPs are also known to favour plant growth and metabolism (Husen and Iqbal 2019). For instance, increase in the amount of an important SM (artemisinin) has been reported in the *A. annua* hairy-root cultures under the exposure of silver NPs. This increase can be linked to the signaling molecule production (Zhang et al. 2013). Silver NPs also have shown a positive impact on synthesis of anthocyanin and flavonoid in *Arabidopsis* plants, as the expression level of genes responsible for their synthesis exhibits up-regulation (Garcia-Sanchez et al. 2015). Enhancement in the content of a steroidal diosgenin and saponin in *Trigonella foenum-graecum* was found after application of silver NPs (Jasim et al. 2017). The higher accumulation of flavonoids and phenolics along with increased callus induction was observed in *Prunella vulgaris,* known for its antiviral features, when cultivated in a medium fortified with NAA along with gold or silver NPs (Fazal et al. 2016). Melatonin, an environment-friendly molecule with significant antioxidant capacity, is present in water hyacinth. This aquatic plant is tolerant to the stress caused by chemical pollutants of water and soil (Tan et al. 2007; Arnao and Hernandez-Ruiz 2006). Moreover, A wide range of chemicals, including fungicides, herbicides and pesticides, also influence the morpho-physiological traits of plants, normally causing negative effects (Bashir et al. 2007a, b; 2014; Bashir and Iqbal 2014; Majid et al. 2013, 2014).

Many plants are capable to withstand the HM contamination of air, water or soil and can thrive well in the polluted environment. Based on their extraordinary capability to absorb and accumulate heavy metals in their tissues, some hyperaccumulator plant species have been identified (Iqbal et al. 2015; Memon 2016). Such plants are being used for phytoremediation, a technique to clean contaminated substrata by using plants. This cost-effective and least disruptive technique of remediation is rapidly gaining ground for removing metal ions from contaminated soil or groundwater in an environment-friendly manner (Jabeen et al. 2009; Vamerali et al. 2010; Ansari et al. 2015). Numerous plants have been studied to assess their capacity to remove heavy metals such as chromium (Diwan et al. 2010b, 2012), arsenic, cadmium, copper, mercury and nickel (Ansari et al. 2013a, b, 2015, 2018, 2021) from the contaminated sites.

2.5 Air Pollutant Stress

Air pollutants together with greenhouse gases constitute a key environmental challenge for medicinal plants. Among the gaseous pollutants, CO_2 and SO_2 are most prominent, having shown a remarkable rise in atmosphere since the industrialization has taken place (Yunus and Iqbal 1996; Yunus et al. 1996; Iqbal et al. 2000a, b; Husen 2021a, 2022d). The issue of the impact of air pollution on medicinal plants began attracting serious attention of researchers early in 1970s. In India, preliminary studies of air pollution versus plant performance were undertaken during the 1980s, dealing with morpho-anatomical changes caused by air pollution in the open-grown herbs and shrubs such as *Achyranthus aspera*, *Cajanus cajan*, *Cassia occidentalis*, *C. tora*, *Cleome viscosa*, *Datura innoxia*, *Lantana camara*, *Phyllanthus rhamnoides* and *Sida spinosa* (Iqbal et al. 1986, 1987a, b; Ahmad et al. 1987; Mahmooduzzafar et al. 1987; Ghouse et al. 1989). Later investigations focused primarily on functional and biochemical analysis of a number of species including *Achyranthus aspera, Croton bonplandianum, Datura innoxia, Peristrophe bicalyculata*, *Phyllanthus rhamnoides* and *Ruellia tuberosa* grown under the load of coal-smoke (with SO_2 as its major constituent) released from thermal power stations (Mahmooduzzafar et al. 1992; Dhir et al. 1999; Husen et al. 1999; Nighat et al. 1999; Ahmad et al. 2004; Husen and Iqbal 2004). Special emphasis was laid on foliar features including the leaf growth, trichome density, stomatal behaviour, chlorophyll biosynthesis, and the net photosynthetic rate (Nighat et al. 2000, 2008; Dhir et al. 2001; Trag et al. 2001, 2002; Aquil et al. 2003; Wali et al. 2004, 2007; Verma et al. 2006; Iqbal et al. 2000a, 2010b), because leaves are affected by the pollutants maximally and almost invariably. However, the major concern about the medicinal plants relates to the quality and quantity of their secondary metabolites as affected by environmental pollution. Production of hyoscyamine in *Datura innoxia* (Singh et al. 2000) and psoralen in *Psoralea corylifolia* (Ali et al. 2008b) was adversely affected by coal-smoke pollution. Composition of seed oils of *Peristrophe bicalyculata* and *Ruellia tuberosa* was changed due to an altered ratio of the component fatty acids under the polluted condition, suggesting thereby that not only the quantity but even the quality of herbal drugs is likely to be affected by the polluted environment (Iqbal et al.

2011b). Efforts have been made to characterize the medicinal plants with controversial botanical identity on the basis of their active ingredients and evaluate the impact of pollution stress on these molecules of therapeutic value (Iqbal et al. 2011a).

Increased CO_2 accelarated the photosynthetic carbon assimilation rates (~31%) across 40 plant species. In C3 species, it caused 20% increase in the above-ground biomass on an average (Ainsworth and Long 2005; Law et al. 2001). However, too high concentrations of CO_2 are injurious for plant health. CO_2 reduced the concentration of nitrogen in vegetative plant parts as well as in seeds and grains, subsequently a decrease of protein levels, increase of total phenolics, tannins and the monoterpene a-pinene were noticed (Idso et al. 2000; Williams et al. 1994). In the case of *Papaver setigerum*, increased level of CO_2 exhibited the enrichment of four alkaloids, namely. Noscapine, morphine, codeine and papaverine. Additionally, increase in CO_2 may result in high plant carbon-nutrient ratios producing surplus of non-structural carbohydrates (Ziska et al. 2008). SO_2, a major air pollutant, has the capability to enter into the plant through roots and stomatal openings during respiration and photosynthesis. It may cause damage to photosystems (Swanepoel et al. 2007), affects stomatal density and perturbations in the efficiency of C-fixation (Chung et al. 2011). On the other hand, sulphur deficiency also hampers plant productivity, as it reduces the uptake and assimilation of nitrate (Kaur et al. 2011). Sulphur transport system in plants has a role in modulating S efficiency (Ahmad et al. 2005a), and even the timing of application of S-fertilizer to plants affects their growth and yield; split doses of S applied at different stages of plant development ensure the best outcome (Ahmad et al. 2005b).

Since the medicinal plants are rich in SMs, they have a significant plasticity to adapt to the changing environments (Bachheti et al. 2021). This may affect the production of SMs, which generally form the basis for the medicinal properties of plants (Mishra 2016). For intance, *Digitalis lanata*, which is used mostly in heart diseases (Rahimtoola 2004), goes richer in digoxin, a cardenolide glycoside, when treated with high CO_2 while the concentration of other three glycosides, namely, digitoxin, digitoxigenin and digoxin-mono-digitoxoside, decreases (Stuhlfauth et al. 1987; Stuhlfauth and Fock 1990). *Hymenocallis littoralis*, normally used as an antineoplastic and antiviral, showed a rise in the concentration of three alkaloids (pancratistatin, 7-deoxynarciclasine and 7-deoxy-trans dihydronarciclasin) in the Ist year and a decline during the subsequent years, when exposed to elevated CO_2 (Idso et al. 2000). In *Ginkgo biloba*, used in dementia and Alzheimer's disease (Weinmann et al. 2010), the flavonoids concentration is affected by the increased CO_2 and O_3, the impact of CO_2 being more dominant. Elevated CO_2 reduced the concentrations of isorhamnetin aglycon and keampferol aglycon. The combined treatment of elevated CO_2 and O_3 also gave similar results, although the elevated O_3 alone caused a decline in isorhamnetin aglycon concentration and a rise in quercetin aglycon concentration (Huang et al. 2010).

The air pollution effect on plant performance is not confined to the primary plant body and its metabolic activities but also affects the secondary growth of woody plants. Periodicity of the lateral meristem (the vascular cambium) may be altered, *i.e.*, the prescribed schedule of the cambial activity and dormancy in a species and, consequently, the pattern of the production of secondary vascular tissues (bark and wood) are changed under the pollution stress (Iqbal et al. 2000b, 2010a, c). It was observed that the production of secondary tissues is not correlated necessarily to the rate of carbon assimilation (photosynthesis) or the amount of photosynthate produced but to the pattern of carbon partitioning, *i.e.*, distribution of photosynthate (Iqbal et al. 2000b, c, 2005; Mahmooduzzafar et al. 2003). The amount of annual wood production as well as the gross structure of wood may change under the stress of air pollution (Gupta and Iqbal 2005; Mahmooduzzafar et al. 2010).

2.6 Nutrient Deficiency Stress

Carbon, nitrogen, calcium, phosphorus and potassium are considered as the major essential mineral nutrients required by plants. These nutrients help plants in maintaining the physical organization, energy generation and molecules production, participate in protoplasm repair, and regulate the metabolic activities and other functions of living cells. These nutrients play important roles in improving the crop yield and maintaining the soil fertility. Nutrient stress has a noticeable effect on the checmical compostion and growth of plant tissues. Production of many secondary plant products is dependent on the growing conditions or the environment that affect the various metabolic pathways responsible for the deposition of the concerned natural products (Ganai et al. 2020). In a study of *Brassica juncea* grown inside the free air CO_2 enrichment rings, elevated [CO_2] showed insignificant impact on the minimal chlorophyll fluorescence (F_0), but the quantum efficiency of photosystem II increased by 3% (Ruhil et al. 2015). The electron-transport rate, photosystem I, photosystem II, and the whole-chain electron-transport rates were enhanced by 8%, while the net photosynthesis rate increased by ≈50%. Moreover, the metabolic pathways of carbon and nitrogen, the two essential elements for plant growth and development, influence each other and affect the gene expression, but information about genes or the mechanism affected by carbon and nitrogen interaction is limited. Attempt has been made to recognize proteins and the encoding genes of the interaction between carbon and nitrogen in Indian mustard. Identification of proteins like PII-like protein, cyclophilin, elongation factor-TU, oxygen-evolving enhancer protein and rubisco activase has provided hints about how the N-efficient cultivars of Indian mustard adapt to low N supply under elevated [CO_2] conditions (Yousuf et al. 2016c). Further, as a macronutrient, calcium contributes to the structure and functions of plants. It helps in maintaining the normal function of membranes and the growth of meristematic tissues and leaf primordia, and in sending signals in response to internal and external indications (Dordas 2009; Price et al. 1994; Naeem et al. 2009). Calcium is supportive in the regulation of plant responses to a range of environmental stresses by contributing either directly or indirectly in plant defense mechanisms. Khan et al. (2010) have reported that the exogenous exposure of calcium improves plant resistance against the drought, heat and salt stresses by regulating the antioxidant enzyme activities, and reducing the membrane lipid peroxidation, thus helping plant cells to survive under a range of environmental stresses.

Phosphorus deficiency hampers plant growth in many ways. P inputs significantly increased the biomass production and the P and Zn accumulation in high- as well as low-Zn-accumulating genotypes of chickpea (*Cicer arietinum* L.). However, higher concentration of P had a negative effect on the features studied, but helped in resisting the low P availability in the soil (Siddiqui et al. 2015a). Zn supply to the soil caused significant increase in growth parameters, although a too high ZN dose was inhibitive. Improvement in growth parameters was evident from pre-flowering stage to post-flowering stage of plant life, except for the leaf area index, which showed a decline in the post-flowering stage. High Zn-accumulating genotype (HZnG) performed better than the low Zn-accumulating genotype (LZnG) at deficient levels of zinc supply (Siddiqui et al. 2016). In another study of chickpea, the HZnG was found to maintain a significantly higher level of chlorophyll, protein, nitrate, leghemoglobin, nitrate reductase, superoxide dismutase, and carbonic anhydrase, in comparison to LZnG under zinc-limiting condition. Zinc supply to the soil improved the situation in both genotypes, more effectively in HZnG (Siddiqui et al. 2015b).

Potassium also affects the metabolic activities of plants. It increased nitrogen assimilation and yield in the case of *Lepedium sativum* (Dhawan et al. 2011). Likewise, sulphur has a role in maintaining plant performance. Cultivar Pusa Jai Kisan of *Brassica juncea* was found to be more sensitive to S deprivation than cv. Pusa Bold (Anjum et al. 2011). Further, based on the study of *Arabidopsis thaliana*, Wadhwa et al. (2012) reported that sulphur metabolites regulate the uptake of sulphate.

2.7 Radiation Stress

Light or radiation is a physical factor, which can influence or stimulate the metabolic activities in plants. Light intensity shows a correlation with the level of phenolics. In the case of *Zingiber officinale* callus, it stimulates production of gingerol and zingiberene (Anasori and Asghari 2008). The impact of diverse environmental situations, like light intensity and irradiance, was observed on cell biomass and production of anthocyanin in *Melastoma malabathricum* culture (Chan et al. 2010). Light irradiation affects artemisinin biosynthesis in hairy roots of *Artemisia annua* and digitoxin formation in *Digitalis purpurea* (Hagimori et al. 1982; Verma et al. 2018). Exposure of *Datura innoxia* to low (5 Gy) dose of gamma radiation caused stimulatory effect on germination of seed and increased the growth rate of root and shoot, stomatal conductance, chlorophyll and carotenoids contents and the net photosynthetic rate. Higher doses proved inhibitory for all these parameters; the negative impact being positively correlated to increase in radiation intensity. However, hyoscyamine content exhibited only irregular and non-significant variation (Aref et al. 2016).

UV-C part of sunlight is totally absorbed by the stratospheric zone layer. Most of UV-B is also absorbed there, and only a small part of this radiation reaches the Earth surface. UV-A radiations are not injurious to living beings. Plants sense UV-B radiation with the help of UVR8 photoreceptor but UV-A might be sensed by cryptochromes and phototropins. Overdoses of UV-B and UV-C radiations negatively influence the plant growth, development and photosynthetic features. It causes overproduction of ROS and development of oxidative stress that can decrease cell viability and lead to cell death. However, low UV-B or UV-C quantities may activate plant acclimatization, including the induced biosynthesis of SMs.

Application of UV-B to *Catharanthus roseus* causes a significant increase in vincristine and vinblastine production, which are used in the treatment of lymphoma and leukemia. Also, the UV-B radiation increases the contents of flavonoid and phenylalanine ammonia-lyase, which are correlated to a decrease in chlorophyll content (Liang et al. 2006). The photoperiod influences endogenous indoleamines (melatonin and serotonin) in cultured *Dunaliella bardawil* (Ramakrishna et al. 2011a, b). O_3 exposures increase the phenolic concentrations in conifers (Rosemann et al. 1991), whereas low O_3 has no effect on the concentration of monoterpene and resin acid (Kainulainen et al. 1998). In *Ginkgo biloba,* O_3 fumigation accelerated terpenes concentrations and reduced those of phenolics in leaves (He et al. 2009). The elevated O_3 reduced the isorhamnetin aglycon concentrations, but increased the quercetin aglycon concentration (Huang et al. 2010).

The commercial value of a medicinal or aromatic plant is reflected by the yield and composition of its SMs or essential oils. Several reports have shown a favourable impact of UV-B radiation on aromatic plants, fetching improvement in the volatile aroma production and inducing changes in the essential oils' chemical composition (Agrawal et al. 2009; Deepti et al. 2022b). Such results have been recorded for many specie including *Mentha spicata* (Karousou et al. 1998) and *Ocimum basilicum* (Chang et al. 2009). Dolzhenko et al. (2010) investigated that application of UV-B was responsible for high contents of menthol and phenolic in peppermint, as the modulation of expression of some genes participating in the essential oil biogenesis was up-regulated by UV-B irradiation. Moderate and low dose UV-B supplementation also enhanced the essential oil yield in *Acorus calamus* and improved its medicinal value by decreasing the content of its potentially toxic constituent, β-asarone (Kumari et al. 2009a). *Cymbopogon citratus* exhibited enhancement in its medicinal value due to higher concetration of z-citral in the essential oil and a larger yield under UV-B irradiation (Kumari et al. 2009b).

3 Conclusion

A large number of abiotic stresses adversely affect plant species, including those with medicinal importance. The symptoms of stress vary in form and intensity. The affected plants undergo a variety of changes, which may cause antagonistic effects on growth features and various other developmental, physiological and metabolic processes of plants. The medicinal plants faced with abiotic stress may have a low relative water content, accelerated ROS production, increased stress injury and cell electrolyte leakage, and a reduction in photosynthetic pigment, root and shoot length, and yield, etc. They may then undergo several morpho-physiological, biochemical and molecular alterations to overcome the negative effects. This includes the biosynthesis of numerous SMs, which is often directly linked to the medicinal importance of the plant. The effect of climate change on medicinal and herbal plants is also important. It is highly desirable to investigate the accumulation of SMs of therapeutic significance under adverse situations. Further, the use of plant cell culture (in vitro) for the production of chemicals and pharmaceuticals has made its significance felt. Moreover, the use of genetic tools in regulation of pathways for secondary metabolism may offer a wider basis for commercial production of SMs. Research on medicinal plants with respect to abiotic stresses and climate change is random and insignificant in comparison with other commercial crop plants. The herbal wealth of great medicinal value deserves a greater attention, as it is a potential source of bio-molecules and nutraceuticals.

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