# The Life of Plants in a Changing Environment

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Edited by

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# PREFACE

Today, plants are faced with many new challenges. The life and growth of plants is in decline due to continuing changes to the environment, mostly caused by different types of stress effects, an increasing human population, and changing food habits. Changes to habitats, stress adaptations, and climate change create new problems with respect to the morphological, physiological, and biochemical aspects of plants and their ability to adapt to these changes during their natural life cycles.

There is no doubt that improvements in the genetic and molecular biology of plants (including crop species) will be key to increasing growth, production, and yields, or changing plant adaptations in response to stress in the future.

The dynamic and increasing body of knowledge concerning the effects of changing environments, stress factors, and their impact on plants and crops has resulted in the compilation of this unique and comprehensive collection, which deals with plants' changing situations and the stresses imposed on them (including vegetable species), in the form of this book for advanced undergraduates, research scholars, teachers, and professionals in the fields of plant adaptation, ecology, and environmental science.

This book consists of 11 chapters prepared by 25 authors from around the country. Chapter 6 emphasizes the impact of plastics on plants and crop productivity, with the hope that this will result in better understanding of plant adaptations to the changing environment.

The induction of oxidative stress in plants is an integral part of plant responses to different environments. Chapter 2 provides knowledge concerning plant growth in relation to oxidative stress in our changing environment. Chapters 4 and 5 focus on how plants adapt and tolerate heavy metal pollution, and how flooding and submergence tolerance is regulated under natural environments during plant life cycles.

Chapters 1 and 7 address different environmental factors affecting secondary metabolites and the interactional effects of UV-radiations and drought.

Chapter 3 emphasizes different aspects of the abiotic stress response. Chapter 8 tackles the intricacies of plant responses to biotic stress with special reference to the metabolomics approach. Chapters 9 and 10 give an overview of how plants react to magnetic nanoparticles and mobile phone radiation in natural environments. Finally, Chapter 11 covers programmed cell death and plant responses to abiotic stress conditions.

Numerous figures and tables appear in this book to facilitate comprehension of the presented material. This book also includes a comprehensive index, a list of illustrations, and a list of acronyms used to further increase the accessibility of the information presented.

All the chapters have been written by experts with extensive experience in their fields of expertise. I am indebted to all the authors for their excellent contributions, which make this book, I think, a valuable resource for different aspects of plant responses to our changing environment. I am aware of the fact that not all the relevant topics in this area could be included in this book due to size limitations.

Finally, I sincerely appreciate the invaluable efforts of each of the contributors who responded to my request for contributions to this volume. Their proficiency and knowledge in their areas of expertise has made this important task possible.

I also wish to acknowledge Rebecca Gladders and James Brittain, who coordinated the publishing process, and Helen Edwards, who has been particularly supportive and helped at various stages of the preparation of this manuscript for publication. I am deeply indebted to all of these people.

Thank you.

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# CHAPTER ONE

# THE IMPACT OF VARIOUS ENVIRONMENTAL FACTORS ON SECONDARY METABOLITES IN PLANTS

D JAIN, P CHAUDHARY, R TRIPATHI AND P JANMEDA

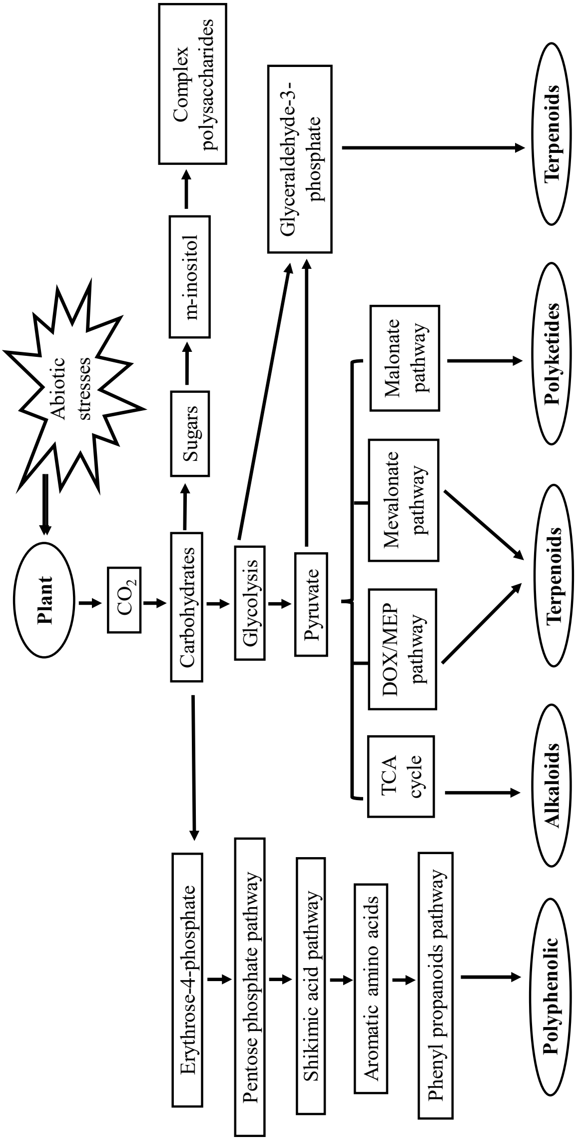
Climate change is responsible for causing changes in various bioactive constituents of plants, including medicinal plants and food crops, across the globe. A number of studies have determined that climate change is not only affecting crop yields, but also bringing about variation in the concentration of secondary metabolites. Plant secondary metabolites (PSM) involve different classes of naturally available compounds and variable biochemical pathways synthesize them under the influence of environmental factors and herbaceous predators. With the help of secondary metabolites, plants can adapt to their changing environments and stress conditions. Despite their significant biological activity, these secondary metabolites are broadly employed in a wide range of industries—as food additives, pesticides, fragrance compounds, cosmetics, and therapeutics. Environmental factors, such as light intensity, humidity, temperature, salinity, and location, etc., are all very important. These factors can be influential through different mechanisms that produce variations in the biogenesis and accumulation of secondary metabolites. Alterations to any of these factors can bring about changes in the content of secondary metabolites. A good understanding of the mechanisms involved in the accumulation, degradation, and synthesis of metabolites is needed for the formulation of future strategies to enhance the productivity, safety, and reliability of secondary metabolites in plants. In this chapter, we present a detailed overview of the possible role of environmental factors in the instability of secondary metabolites in plants.

# Introduction

Secondary plant metabolites can be described as compounds that play no specific role in the regulation of life processes in the host plant; they are, however, required by the plant for interacting with external stimuli in defense and adaptation (Isah et al., 2019). In crop plants, different types of secondary metabolites (SM) are devised from primary metabolites with different physiological functions.

These SMs play an important role in the establishment of a strong relationship between plants and the environment in terms of their fitness and survival, making these compounds valuable as primary metabolites (Kliebenstein et al., 2012). They are used by the host plant to provide a defense against pathogenic organisms and herbivores (War et al., 2012). They also contribute to the dynamic colour, taste, and odour of plants. Secondary metabolites are a common source of material for pharmaceuticals, flavourings, food additives, and other related industrial uses. Chemicals such as nitric acid, jasmonates, polyamines, salicylic acid, abscisic acid, and calcium are used in the stress responses of the host plant. The generation of these compounds is limited and mainly reliant on the developmental and physiological stage of the host plant (Ramakrishna et al., 2011).

Abiotic stresses influence plant metabolism. When crop plants are challenged by abiotic stresses, the results include a reduction in various morphological features, such as root volume, number of branches, leaf area, leaf number, and height, etc., further affecting the biomass of the plants (Fahad et al., 2017). In normal environmental conditions, the production of bioactive metabolites is low, whereas metabolite production is greater when plants encounter abiotic stresses. The accumulation of phenolic and terpenoid compounds in plants has been found to increase under stress conditions. The concentration of various other metabolites is strongly dependent on the growing conditions. By manipulating the metabolic pathways and expression of certain genes associated with the expression of natural bioactive compounds, the synthesis of secondary metabolites has been shown to be heightened in response to different abiotic stresses (Kumar et al., 2018). As such, this chapter aims to summarize the biosynthesis, creation, production, and importance of variable secondary metabolites in host plants in response to different abiotic stresses.




**1.** Pathways for the production of variable secondary metabolites in plants.

## Expression of secondary metabolites in plants

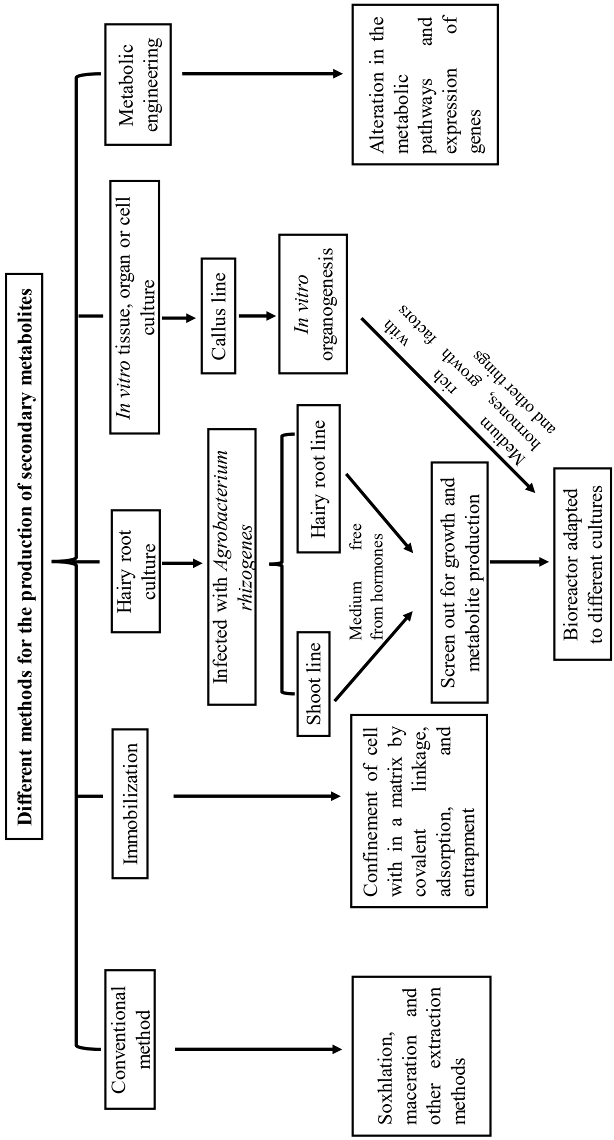
The secondary metabolites of plants can be categorized into three types on the basis of their synthesis: terpenoids, phenolics, and alkaloids. It has been determined that terpenoids are synthesized via the mevalonic and DOX/MEP pathway, phenolic compounds are formed via the malonic acid and shikimic acid pathway, and alkaloids are synthesized from an aromatic amino acid in the shikimic acid pathway and from aliphatic amino acids in the tricarboxylic acid cycle (Parsaeimehr et al., 2011) [**1**].

## Creation of secondary metabolites in plants

A number of components, including the living creatures present, the edaphic conditions, and the season/atmosphere, have been found to affect the presence or lack of some secondary metabolites in medicinal plants (Sampaio et al., 2016). Another factor influencing the formation of secondary metabolites is the interaction of insects and plants. For example, many medicinal plants require the help of pollinators to cross-pollinate. In an open space, the wind can do the job, but in woods where herbs and bushes are found under the canopies of the trees, there is insufficient breeze for their fertilization. To attract pollinating bugs, the plant produces a pleasant smell and provides dust and nectar as food. Dust and pollens are a common source of nourishment for birds and insects (Brittain et al., 2014) and many plants contain an advanced blossom part for fertilization with the help of bugs. In return, these creatures reside on the plants. They lay their eggs on them and when they hatch, the hatchlings start feeding on the leaves. The activity of these hatchlings disturbs the plant and results in the production of some dangerous compounds (Jabr et al., 2013). As such, unfavourable abiotic conditions stress the plants and in return the plants respond to these stresses by producing certain secondary phytochemicals (Biology et al., 1988).

## Production of secondary metabolites

The secondary metabolites of a plant are a unique resource for useful chemicals, food additives, and pharmaceuticals. They are employed in other areas also. Direct extraction and chemical synthesis are commonly used to get these metabolites. Plant cell cultures and metabolic engineering have been suggested as potential alternatives for the production of metabolites that are hard to obtain from extraction and synthesis (Tiwari et al., 2015) [**2**].




**2.** Different methods for the production of secondary metabolites from plants.

- **Conventional method**

  The conventional method is based on the extraction of phytochemicals from plant tissues using various procedures such as supercritical and solvent steam extraction.

The latest advancements in fermentation technology, enzymology, and molecular biology have shown that these systems are important for the *in vitro* production and synthesis of secondary metabolites (Hussain et al., 2012). The main process includes:

- **Immobilization method**

  Confinement of biocatalyst or cell within a suitable matrix by covalent linkage, adsorption, and entrapment. Under favourable physicochemical conditions, and with the addition of a specific substrate, the desired bioactive constituents are synthesized. Immobilization with an appropriate bioreactor system allows many advantages, such as the continuous operation of the process, but for the creation of an immobilized plant cell culture, artificially or naturally induced seepage of accumulated metabolites into the neighboring medium is required.

- **In vitro tissue, organ, and cell culture methods**

  Tissue and plant cell cultures can be routinely developed under aseptic conditions from explants, from samples of meristem, roots, stem, and leaves, etc., both for the extraction and the multiplication of secondary metabolites. Hairy root, cell suspension, callus, root, and shoot cultures can all be utilized for the creation of metabolites of interest. Localized metabolites can be produced through suspension or callus cultures, whereas for those metabolites confined to a specific gland or part, organ cultures and differentiated micro-plants can be chosen. The quantity of secondary metabolite formation in cell cultures can be improved by treating the plant cells with abiotic and biotic elicitors. Yeast extract, fungal carbohydrate, and methyl jasmonate are the primarily utilized elicitors (Thirumurugan et al., 2018).

- **Hairy root cultures**

  Hairy root cultures involve the inoculation of plant roots with *Agrobacterium rhizogenes* and other microorganisms (arbuscular mycorrhizal fungi) for the production of secondary metabolites. The phenotype of the hairy root is characterized by genetic stability, lateral branching, a lack of geotropism, fast growth, and hormone-independent synthesis. The secondary metabolites obtained after the infection of the host plant with *A. rhizogenes* and AMF are similar to those that are synthesized in the intact roots of the plant and with the same or even greater yield (Hussain et al., 2012; Chaudhary et al., 2019).

- **Metabolic engineering**

  Metabolic engineering involves making purposeful and targeted changes to metabolic pathways for the better understanding and use of these pathways for supramolecular assembly, energy transduction, and chemical transformation. In a number of cases, the number of secondary metabolites is too low to be used for commercial purposes and metabolic engineering provides several strategies to decrease catabolism, block competitive pathways and feedback inhibition, increase the flux of carbon through the overexpression of certain genes in biosynthetic pathways, and upgrade the productivity of metabolites in plants (Hussain et al., 2012; Gonçalves et al., 2018).

## Importance of secondary metabolites

Plants struggle to survive for an extended period during their establishment. Gradually they gain the ability to resist stressful conditions through the production of different types of secondary metabolite with variable bioactivities. These metabolites play a crucial role in the pharmaceutical, food, and dye industries, defend the host plant against various pathogenic organisms with other competing plants, and facilitate reproduction and pollination. Some essential secondary metabolites are listed in [**3**].

**3.** Importance of secondary metabolites to various industries.

| Plant species | Secondary metabolites | Uses/Applications | References |
|---|---|---|---|
| Cactus and *Linum usitatissimum* | Mucilage | Demulcent | Hussein *et al*., 2018 |
| *Althaea officinalis* | Marshmallow | Cough suppressant | |
| *Origanum compactum*, *Coriandrum sativum*, *Artemisia herba-alba*, *Cinnamomum camphora*, *Mentha piperita* | Carvacrol and thymol, Linalol, α and β-thuyone and camphor, 1,8-cineole, Menthol and menthone | Used as fragrances in food industry, local anesthetic remedy, spasmolytic, anti-inflammatory, sedative, analgesic, antimicrobial and antiseptic | |
| *Simmondsia chinensis* | Liquid wax and jojoba wax | Wound healing, anti-aging, and anti-inflammatory activity | |
| *Linum usitatissimum* | Fixed oil | Decreases the risk of cardiovascular diseases and atherosclerosis | |
| *Quassia amara* | Quassinoids | Insecticidal property | |
| *Boswellia carterii* | β-boswellic acid and α-boswellic acid | Anti-rheumatic and anti-inflammatory activity | |
| *Glycyrrhizin glabra* | Glycyrrhizin | Antitussive agent, treat cirrhosis, cheonic and hepatitis | |
| *Bupleurum falcatum* | Saponins | Anti-inflammatory property | |
| *Catharanthus roseus* G. | Vinblastine | Diabetes | |

| | | | |
|---|---|---|---|
| *Catharanthus roseus* L. | Vincristine | Nephroblastoma, lymphoma, neuroblastoma, rhabdomyosarcoma, and acute lymphatic leukemia | Seca *et al*., 2018 |
| *Vicia ervilla, Citrus aurantium, Glycyrrhiza glabra* | Apigenin | Anti-infection, antiviral, and anticarcinogenic activity | Parsaeimehr *et al*., 2011 |
| *Fragaria* spp. | Fisetin | Anti-oxidant, anti-carcinogenic and anti-inflammatory activity | Parsaeimehr et *al*., 2011 |
| *Taxus brevifolia* Nutt. | Paclitaxel | Anticancer activity in the cure of lung and breast cancer | Seca *et al*., 2018 |
| *Euphorbia peplus* L. | Ingenol mebutate | Antitumor component | Seca *et al*., 2018 |
| *Curcuma longa* L. | Curcumin | Chemo sensitizing, chemotherapeutic, anti-oxidant, and anti-inflammatory activity | Seca *et al*., 2018 |
| *Chrysanthemum* species | Terpenes | Commercial insecticides | Pagare *et al*., 2015 |
| *Rauwolfia serpentine* | Reserpine | Treatment of thyrotoxicosis, tachycardia, and hypertension | Lobay *et al*., 2015 |
| Cinchona tree | Quinine | Anti-malarial | Achan *et al*., 2011 |
| *Cassia tora* L. | Rotenoids | Larvicidal activity | Vats *et al*., 2018 |
| *Arctostaphylos uvaursi* | Phenolic content | Diuretic and antimicrobial activity | Hussein *et al*., 2018 |

| | | | |
|---|---|---|---|
| *Capsicum* spp. | Capsaicinoids | Analgesic, rubefacient, and circulatory activity | Hussein *et al.*, 2018 |
| *Vaccinium oxycoccos* | Tannin-containing Juice | Urinary antiseptic | Hussein *et al.*, 2018 |
| *Atropa belladonna*, *Datura stramonium*, *Daphne mezereum*, *Ruta graveolens*, *Aesculus hippocastanum* | Coumarins | Anti-alzherimer's, anti-cancer, anti-coagulant, and anti-inflammatory activity | Hussein *et al.*, 2018 |
| *Polygala nyikensis* | Xanthones | Antifungal activity | Hussein *et al.*, 2018 |
| *Cedrus deodara* | Wikstromal, matairesinol, dibenzyl butyrolactol | Cytotoxic activity | Hussein *et al.*, 2018 |
| *Solanaceae* plant family | Nicotine | Anti-inflammatory, insecticidal, antiherbivore, and stimulant activity | Kabera *et al.*, 2014 |
| Tomato plants | Tomatine | Antifungal, anticancer and immune effect | Kabera *et al.*, 2014 |
| *Papaver somniferum* | Codeine | Act as CNS, used in acute pulmonary edema | Kabera *et al.*, 2014 |
| *Polypodium leucotomos* Hook. | Caffeic acid, ferulic acid, and chlorogenic acid | Used as sunscreen | González-Minero *et al.*, 2018 |
| *Camellia sinensis* L. | Vitamin C | Inhibit peroxidation of lipid | González-Minero *et al.*, 2018 |

| | | | |
|---|---|---|---|
| *Vitis vinfera* L. | Polyphenols | Inhibit peroxidation of lipid | González-Minero *et al.*, 2018 |
| *Talaromyces verruculosus* | Red pigment | Textile industry | Chadni *et al.*, 2017 |
| *Vanilla planifolia* | Vanillin | Flavoring agent | Kallscheuer *et al.*, 2018 |
| *Curcuma longa* | Curcumin | Flavoring agent | Kallscheuer *et al.*, 2018 |

## Influence of environmental stress on plant development

Across the globe, plants are subject to different abiotic stresses, which affect agricultural productivity. These abiotic factors are associated with each other and can appear in the form of plant cell homeostasis, malnutrition due to ion distribution, and osmotic stress. Productivity and growth rates are greatly impacted due to alterations in the expression of groups of genes. As such, recognizing which genes are responsible for the control of abiotic stress is necessary to understand the influence of these abiotic stresses on crop plants (Gull et al., 2019).

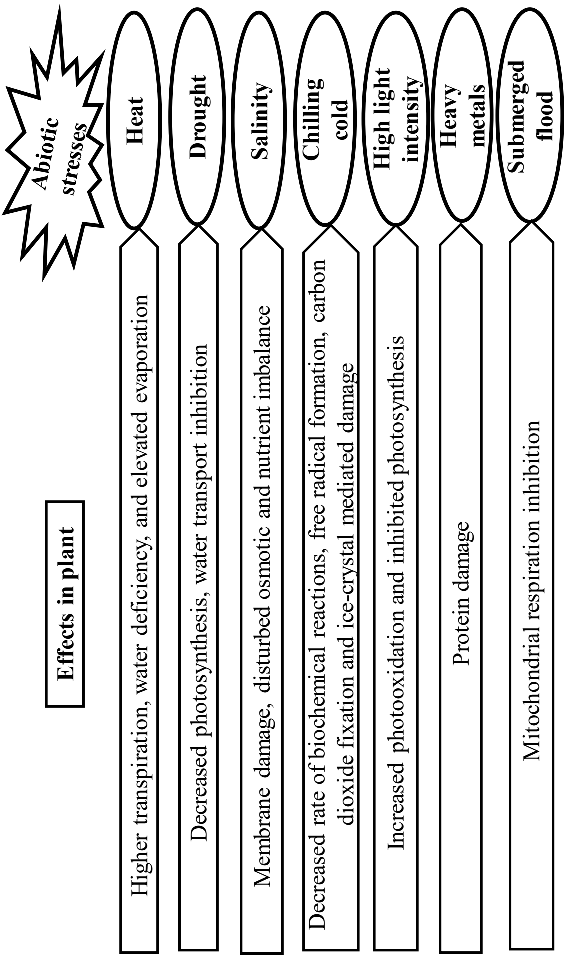
## Environmental factors

Plants are affected by various environmental factors in achieving the sustenance necessary for life and are thus affected by different abiotic and biotic stimuli, leading to the production of particular bioactive constituents (Zhi-lin et al., 2007). Plants of similar species that are cultivated in variable environmental conditions may show variation in the yield of secondary metabolites. Biotic and abiotic factors cause biotic and abiotic stresses, respectively, in host plants as a result of unfavourable conditions. In order to counteract these stresses, plants produce dynamic secondary metabolites. As a result, environmental factors are key factors driving the synthesis of plant metabolites. Abiotic stresses are caused by the composition and type of soil, temperature, water availability, and light intensity, etc., which all influence the productivity and quality of plants.

In contrast, biotic stress is induced by living organisms such as parasites, fungi, viruses, and bacteria (Radusiene et al., 2012). Chemicals, such as growth regulators (NAA, IAA, and 2,4-D), metals (Mn, Zn, Fe, Cr, Co, Cd, and Ni, etc.), pesticides, pollutants, and gaseous compounds and radiation (UV and simple light) also contribute to abiotic stress in host plants (Ramakrishna et al., 2011). Plants do not acquire an immune system and are not able to move like animals. They gain tolerance of these unfavourable conditions through the accumulation of bioactive metabolites**.**

## Impact of environmental stress factors in plants

Abiotic stresses constitute the primary limiting factor for the sustainable productivity of crops. Plants overcome these adverse effects, born of the edaphic and environmental conditions, through intrinsic biological mechanisms. Plants require minerals, nutrients, carbon, water, and light for reproduction, development, and growth. Adverse conditions (above or below the optimal level) restrict plant development and growth. Unfavourable factors in an ecosystem include salinity, drought, and low or high temperatures, all of which create complex stress conditions. Plants respond to these stresses in a variety of ways (Ahmad et al., 2015; Jiang et al., 2016). Commonly, the effects of stressful growing conditions appear at the cellular level first, before appearing at the physiological level. Prolonged stress due to the unavailability of water decreases leaf size, stomatal openings, and water potential; delays fruiting and flowering; restricts plant productivity and growth; suppresses root growth; and reduces the viability, number, and size of seeds (Xu et al., 2016). Exposure to high and low light intensity reduces physiological processes and unfavourably influences the development and growth of plants. Extreme light intensity increases the production of reactive oxygen species, which manipulate enzymes and other biomolecules (Li et al., 2009). Significant increases and decreases in temperature are primary causes of loss of productivity (Pareek et al., 2010). Several edaphic factors, such as anthropogenic perturbation, contamination by pollutants, and alkalinity, acidity, and salinity of soil greatly affect the development and production of crops (Bui et al., 2013; Emamverdian et al., 2015) [**4**].




**4.** Effect of different abiotic stresses in plants.

## Abiotic factors

Throughout their ontogeny, plants connect with their environment and come into conflict with numerous components, including light, soil, water, temperature, and chemical substances like fertilizers and minerals, which are all necessary for plants to grow and survive properly. However, plants are also impacted by a greater or lesser number of these abiotic factors, contributing to differences in their development or accumulation of PSMs.

1. **Light**

This factor concerns photoperiod (duration), direction (frequency or wavelength), and intensity (quantity). Reacting to light exposure, plants receive significant economic and consumption benefits from various secondary metabolites, including flavonoids, triterpenoids, and phenolic compounds due to their well-recognized antioxidant properties. A short daytime of light exposure will result in a reduction of about 40 % of caffeoylquinic acids and also a roughly double reduction in the content of flavonoid aglycones compared to a long daytime of light exposure (Yang et al., 2018). As such, light intensity has a substantial influence on the accumulation of PSMs, as listed in [**5**].

**5.** Effect of light on the production of various secondary metabolites in plants.

| Plant species | Compounds | Conditions | Reference |
|---|---|---|---|
| *M. glomerata* | Coumarins | Light irradiation | de Castro *et al*., 2006 |
| *Artemisia annua* | Artemisin | Light irradiation | Liu *et al*., 2002 |
| *Panax quinquefolius* | Higher levels of ginsenosides | Longer light exposure | Fournier *et al*., 2003 |
| *Vaccinium myrtillus* | Flavonoid biosynthesis pathway activation | Continuous solar radiation | Jaakola *et al*., 2004 |
| *Catharanthus roseus* | Vinblastine, vincristine, Flavonoid | UV-B light | Bernard *et al*., 2009; Dixon and paiva, 1995 |
| *Vitis vinifera* | Stilbene | UV-C irradiation | Wang *et al*., 2010; liu *et al*., 2010 |
| *Centaurea cyanus* | Anthocyanins | UV-C irradiation | Kakegawa *et al*., 1991 |
| *Hordeum vulgare* | Flavonoids | UV-B | Liu *et al*., 1995 |

| | | | |
|---|---|---|---|
| *Cucumis sativus* | Polyamines | UV-B | Kramer *et al.*, 1991 |
| *Picea abies* | Flavonols | UV-B irradiation | Fischbach *et al.*, 1999 |
| *Digitalis purpurea* | Digitoxin | Light irradiation | Hagimori *et al.*, 1982 |
| *Melastoma malabathric* | Anthocyanins | Light irradiation | Chan *et al.*, 2010 |
| *Ocimun basilicum* | Rosmarinic acid accumulation | Exposure to red light (600–700 nm) | Shiga *et al.*, 2009 |
| *Zingiber officinale* | Gingerol and zingiberene | Light | Anasori *et al.*, 2008 |
| *Taxus cuspidate* | Taxol and baccatin III | White light | Fett-Neto *et al.*, 1995 |

## 2. Temperature

Good plant development relies on an ideal environment. Lower and higher temperatures have a detrimental influence on plants commsurate with heat and cold tension (Yadav, 2010). Several studies have shown an improvement in PSM biosynthesis as well as a decline in secondary metabolite in reaction to high temperatures. Cold stress concerns low temperatures (< 20℃), which impact plant growth and development and considerably limit productivity (Chinnusamy et al., 2007). Low temperatures retard plant growth, contributing to a decreased rate of photosynthesis and a lower yield of *Capsicum annuum*. Low temperatures often contribute to specific molecular, physiological, and biochemical alterations in plants that render them immune to cold exposure, which is known as cold acclimation (capacity to thrive and avoid injury under low-temperature stress). Research has revealed that the pressure of cold has a significant impact on variation in PSM content, as listed in [**6**].

**6.** Effect of temperature on the production of various secondary metabolites in plants.

| **Plant species** | **Compounds** | **Conditions** | **Reference** |
|---|---|---|---|
| *Panax quinquefolius, P. ginseng* | Ginsenosides | High temperature | Yu *et al.*, 2005; Jochum *et al.*, 2007 |
| *Hypericum perforatum* | Hypericin, hyperforin | Low temperature | Zobayed *et al.*, 2005 |
| *Hemerocallis sp.* | Suberin or lignin | - | Griffith *et al.*, 2004 |
| *Pinus pinaster* | Endogenous jasmonates | - | Pedranzani *et al.*, 2003 |
| *Rhodiola crenulata* | Melatonin | - | Zhao *et al.*, 2011 |
| *Medicago sativa* | Putrescine | - | Nadeau *et al.*, 1987 |
| *Melastoma malabathricum* | Anthocyanin | - | Chan *et al.*, 2010 |
| *Artemisia spp.* | Higher levels of artemisin | Lower temperature | Wallaart *et al.*, 2000; Brown *et al.*, 2010 |
| *Nicotiana tabacum* | Higher levels of anthocyanins | Lower temperature | Huang *et al.*, 2012 |

### 3. Heavy metals

Heavy metals can induce shifts in the metabolism of plants and affect the production of photosynthetic pigments, proteins, sugars, and non-protein thiols. Metals can enhance the development of bioactive compounds by modifying the dimensions of secondary metabolism (Verpoorte et al., 2002). Several metals, like iron (Fe), cobalt (Co), silver (Ag), and nickel (Ni), have been shown to exhibit the synthesis of secondary metabolites in plant varieties (Zhao et al., 2001). The production of secondary metabolites is affected by various metal ions, such as oxalate, $Eu^{3+}$, $La^{3+}$, $Cd^{2+}$, and $Ag^{+}$, etc. (Marschner, 1995), as listed in [**7**].

**7.** Effect of heavy metals on the production of various secondary metabolites in plants.

| Plant species | Compounds | Reference |
|---|---|---|
| *Taxus chinensis* | Taxol | Groppa *et al*., 2001 |
| *Amaranthus caudatus* | β-cyanins | Obrenovic *et al*., 1990 |
| *Lepidium sativum* | Lepidine | Saba *et al*., 2000 |
| *Perovskia abrotanoides* | Tanshinone | Arehzoo *et al*., 2015 |
| *Datura stramonium* | Sesquiterpenoid, lubimin | Threlfal *et al*., 1988; Furze *et al*., 1991 |
| *Brassica juncea* | 35 % increase in oil content | Singh *et al*., 2005 |
| *Lithospermum sp.* | Shikonin | Mizukami *et al*., 1977 |
| *Digitalis lanata* | Digitalin | Ohlsson *et al*., 1989 |
| *Beta vulgaris* | Betalains | Trejo-Tapia *et al*., 2001 |
| *Brugmansia candida* | Scopolamine, Hyoscyamine | Angelova *et al*., 2006 |
| *Salvia castanea* | Tanshinone | Li *et al*., 2016 |
| *Datura metel* | Atropine | Shakeran *et al*., 2015 |
| *Vitis vinifera* | Resveratrol | Cai *et al*., 2013 |
| *Ammi majus* | Xanthotoxin | Purohit *et al*., 1995 |
| *Bacopa monnieri* | Bacoside | Sharma *et al*., 2015 |
| *Beta vulgaris* | Betalain | Savitha *et al*., 2006 |
| *Dioscorea bulbifera* | Diosgenin | Narula *et al*., 2005 |
| *Atropa belladonna* | Tropane alkaloids | Lee *et al*., 1998 |
| *Hyoscyamus albus* | Phytoalexin | Mader *et al*., 1999 |

## 4. Water

Water is an essential molecule of plant physiology, serving as the means of transportation of active ingredients and nutrients. As water flow is reduced, or transpiration in the plant rises, water stress is induced, i.e. from drought and salinity stress.

### 4.1 Drought

Drought sees a lack of water taken up by a plant with a reduction in water capability and turgidity in such a way that its physiological and pathological activities are affected (Tippmann et al., 2006; Lisar et al., 2012). It inhibits profitability, biosynthesis, and photosynthesis, changing the plant's biochemical characteristics (Zobayed et al., 2007; Aimar et al., 2011). Several PSMs encourage plants to flourish. The growth of PSM production in several medicinal plants, such as *Hypericum perforatum*, *C. roseus*, and *Artemisia annua*, has been observed as a consequence of extreme drought stress, as listed in [**8**]. Studies have shown that water plays a critical role in plant metabolism and physiological activities and can modify the biosynthesis and concentrations of PSMs (Azhar et al., 2011).

**8.** Effect of drought on the production of various secondary metabolites in plants.

| Plant species | Compounds | Conditions | References |
|---|---|---|---|
| *Trachyspermum ammi* | Increases chlorophyll and total phenolic content | Water scarcity | Azhar *et al.*, 2011 |
| *Matricaria chamomilla* | Reduce oil content | Salinity and drought stress | Razmjoo *et al.*, 2008 |
| *Artemisia* | Artemisinin | Scarcity of water increases | Zobayed *et al.*, 2007 |
| *Hypericum brasiliense* | Betulinic acid, quercetin, and rutin | Scarcity of water increases | Zobayed *et al.*, 2007 |
| *G. longituba* | Total flavonoids content | Water deficiency | Zhang *et al.*, 2012 |
| *Ocimum basilicum and Ocimum americanum* | Carbohydrates, essential oil, proline, nitrogen, Phosphorus, potassium and protein content | Water stress | Khalid *et al.*, 2006 |
| *Salix sp.* | Flavonoids, phenolics | Drought | Larson *et al.*, 1988 |
| *Stevia rebaudiana* | Steviol glycosides | Polyethylene glycol induce drought | Pratibha *et al.*, 2015 |
| *Hypericum adenotrichum* | Hypericin, pseudohypericin | Polyethylene glycol induce drought | Omer *et al.*, 2013 |

| | | | |
|---|---|---|---|
| *Hypericum perforatum* | Hypericin, hyperforin | Water and osmotic imbalance | Pavlik *et al*., 2007 |
| *Bupleurum Chinese* | Saikosaponins | Water stress | Zhu *et al*., 2009 |
| *Salvia miltiorrhiza* | Salvianolic acid | Water stress | Liu *et al*., 2011 |
| *Prunella vulgaris* | Rosmarinic, ursolic, and oleanol | Drought stress | Chem *et al*., 2011 |
| *Glycyrrhiza uralensis* | Glycyrrhizic acid | Water stress | Li *et al*., 2011 |
| *Glycine max* | Trigonelline | Drought stress | Cho *et al*., 2003 |
| *Brassica napus* | Glucosinolates | Drought stress | Jensen *et al*., 1996 |
| *Lupines angustifolius* | Chinolizidin alkaloids | Drought stress | Christiansen *et al*., 1997 |
| *Camellia sinensis* | Epicatechins | Drought stress | Hernaendez *et al*., 2006 |
| *Hypericum brasiliense* | Betulinic acid, rutine | Drought stress | De Abreu *et al*., 2005 |
| *Helianthus annuum* | Chlorogenic acid | Drought stress | De moral *et al*., 1972 |
| *Salvia miltiorrhiza* | Rosmarinic acid | Drought stress | Liu *et al*., 2011 |
| *Papaver somniferum* | Morphine alkaloids | Drought stress | Szabo *et al*., 2003 |
| *Quercus ilex* | Lower monoterpene emissions | Drought stress | Lavoir *et al*., 2009 |

### 4.2 Salinity

Increased soil salinity and many other factors, like heavy rainfall, and low soil temperature create stress for plants, despite water accessibility. High salt concentration, especially due to ions such as $Na^+$ in the soil, can lessen water and nutrient absorption, as well as the growth, production, photosynthesis, and respiration of plants. This can dehydrate the plant's cell membranes due to the removal of water from the cytoplasm, which causes oxidative pressure (Tippmann et al., 2006). The secondary metabolite concentrations in plants may be attributed to variations in ionic and osmotic stress caused by salt tolerance (Ramakrishna et al., 2011). Many plants, such as *M. pulegium*, *Mentha suaveolens*, *Origanum vulgare*, *Mentha piperita*, *Majorana hortensis*, *Thymus maroccanus*, *M. chamomilla*, *Salvia officinalis*, and *T. ammi* show a reduction in essential oil production under salt stress. In contrast, some plants, like *Satureja hortensis*, *S. officinalis*, and *Matricaria recutita* show an increase in the production of essential oil content under salt stress (Said-Al Ahl et al., 2011). These studies have clearly shown that salinity encourages PSM accumulation, as listed in [**9**].

**9.** Effect of salinity on the production of various secondary metabolites in plants.

| Plant species | Compounds | Conditions | Reference |
|---|---|---|---|
| *Rauvolfia tetraphylla* | Reserpine | Salt stress | Said-Al Ahl *et al.*, 2011 |
| *C. roseus* | Vincristine alkaloids and indole alkaloids | | Said-Al Ahl *et al.*, 2011; Misra *et al.*, 2006; Fatima *et al.*, 2015 |
| *Ricinus comunis* | Ricinine alkaloids | | Said-Al Ahl *et al.*, 2011 |
| *Solanum nigrum* | Solasodine | | Said-Al Ahl *et al.*, 2011 |
| *M. chamomilla* | Phenolic acids (protocatechuic, chlorogenic and caffeic acids) | | Kovácik *et al.*, 2009 |
| *Nigella sativa* | Enhancement of Phenols | | Bourgou *et al.*, 2010 |
| *Menthe pulegium* | Enhancement of Phenols | | Queslati *et al.*, 2010 |
| *Plantago ovata* | Proline, flavonoids and saponins | | Haghighi *et al.*, 2012 |