ALLELOPATHY AND CHEMICAL DEFENSE

Franz Hadacek
Department of Chemical Ecology and Ecosystem Research, University of Vienna, Austria

Keywords: Secondary metabolites, induced, constitutive, plants, animals, bacteria, fungi, biotic stress, biodiversity, marine, terrestrial

Contents

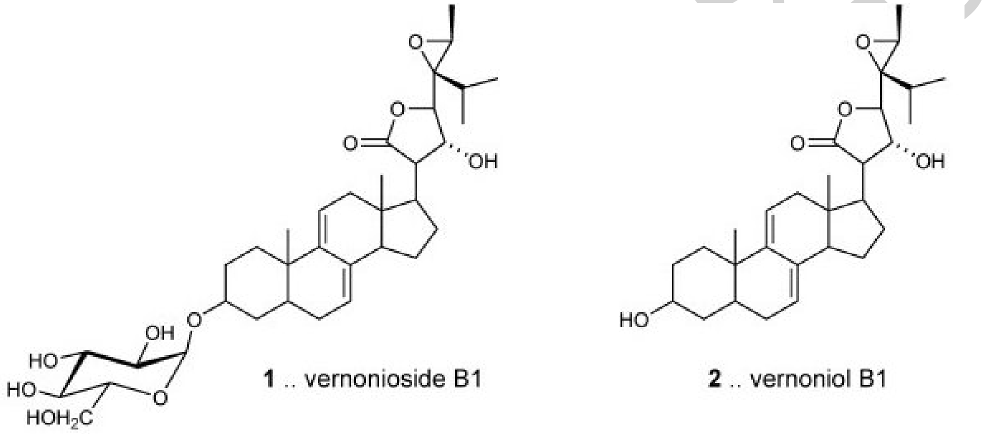
Summary

Secondary metabolites contribute as allomones to the chemical defense of the producing organism. This represents a central paradigm of the defense hypothesis. However, at a more close inspection, we observe that compounds that confer to the chemical defense against a range of potential predators, may be also used by a more specialized one as signals to locate its prey (kairomone). In the course of the closely linked evolution of plants and herbivore insects, this has happened many times. Further, such phenomena are not restricted to plants and herbivore insects; we can find them in many organisms, from prokaryotes to eukaryotes. Only vertebrates do not rely, or better have not to rely on secondary metabolites to ward of pathogens and predators, because they have developed an immune system that takes over the job. In this chapter, the characteristics of secondary metabolite accumulation in various groups of organisms will be reviewed and the mechanisms of their biosynthesis will be outlined briefly. Secondary metabolites can travel along food chains, e.g. the poison arrow frogs usually obtain their skin alkaloids from ants and beetles they feed on as their diet. Biological activity is the main phenomenon which allows secondary metabolites to determine the outcome of biotic interactions. These molecules can bind to a receptor pocket of a protein, change or inhibit the functionality of the enzyme, or it can interfere with the redox equilibrium of the cell. Oxygen radicals represent an intra- and intercellular communication system that allows organisms to cope with biotic and abiotic stress. Finally, in conclusion of this survey, a hypothesis will be introduced that predicts that secondary metabolites do not only determine the outcome of biotic actions but are essential negative feedbacks that facilitate gradients for the coexistence of species with variable susceptibility toward this feedback.

1. Introduction

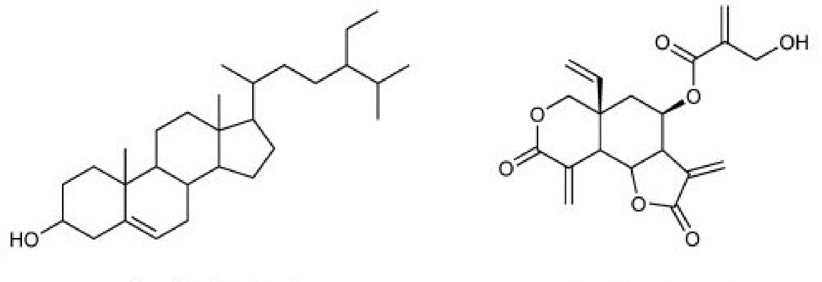
Chemical defense of organisms occurs both in terrestrial and aquatic habitats. The author is more familiar with terrestrial habitats, and thus the majority of all presented examples will accrue from there.

Dried skins of frogs and toads have been used in China to treat heart insufficiencies already more than 4000 years ago. On the other hand, in Africa and South America people learned to prepare poisonous arrows from the same source. Awareness that plants and animals may contain chemical compounds that, depending on the applied dose, exert either poisonous or healing properties existed most probably long before anything was written down. It was the physician Theophrastus Philippus Aureolus Bombastus von Hohenheim, better known as Paracelsus (1493–1441), who bequeathed us the often-cited dictum "dosis sola facit venenum" (the dose makes the poison).



1 .. vernonioside B1

2 .. vernoniol B1



3 .. β-sitosterol

4 .. vernonidal

Figure 1. The saponine vernonioside B1 (1), its steroid triterpene aglycon vernonidol B1 (2), and the sesquiterpene lactone vernonidal (3) represent characteristic secondary metabolites of the pith of *Vernonia amygdalina* that is chewed by wild chimpanzees. The steroid triterpene β-sitosterol (4) confers stability to membranes and is omnipresent in plants.

However, pharmaceutical utilization of plants seems not at all restricted to humans alone: Chimpanzees were observed to chew the pith of young twigs of the composite *Vernonia amygdalina* containing the steroid glycoside vernonioside B1 (1, Figure 1) and its aglycone vernoniol B1 (2, Figure 1), two specific metabolites of that plant. Both compounds displayed remarkable antischistosomal activities in *in vitro* assays and may thus benefit individuals that suffer from intestinal worms. They represent derivatives of the widely occurring steroid triterpenes β-sitosterol (3, Figure 1) that confers stability to membranes in plants. The pith has a repellent bitter flavor. Sesquiterpene lactones, such as vernonidal (4, Figure 1), were found to cause the latter effect. The investigating scientists hypothesized that the highly bitter constituents may play an important role as signals to the chimpanzees by guiding their choice to the appropriate plant and plant part respectively. Additionally, they might also help to control the amount of intake. Such findings imply that secondary plant metabolites mediate interactions between an animal and a plant in a complex manner.

Today we know that compounds with a molecular weight mostly well below 1000 cause those effects, and which are addressed as natural products, secondary metabolites, or allelochemicals, depending if the research has a more pharmaceutical or ecological background. The term secondary metabolites established itself in the first half of the 20th century in most of the textbooks in contrast to primary metabolites. The latter include all those low molecular size compounds that are essential to maintain life, such as sugars, organic acids, and those amino acids which are used to synthesize proteins. Presently, estimates of secondary metabolites in plants alone exceed more than 500.000 structures.

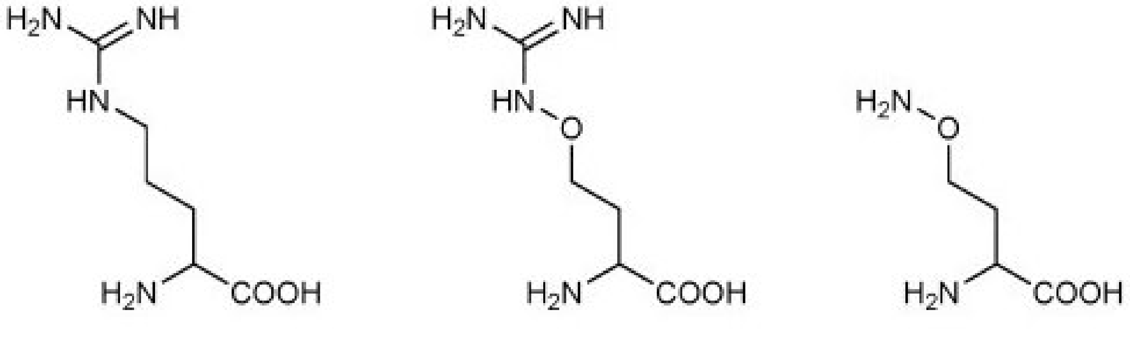
However, the ability to synthesize such molecules is not restricted to plants. Already bacteria, unicellular prokaryotic organisms, are capable of synthesizing toxic secondary metabolites and proteins that are cause of many bacterially induced diseases in higher organisms, such as plants and animals. However, there exists one fundamental difference between the plants and microorganisms: only plants, to a lesser degree some invertebrates, are capable of accumulating secondary metabolites in larger amounts in specialized cells or tissues. Bacteria and fungi, by contrast, secrete secondary metabolites into their environment, partly also as a measure to protect themselves from their toxicity. In plants again, the accumulation in specifically compartmented cells and tissues serves as protection against auto-toxicity. Animals, and here especially invertebrates, are also capable of synthesizing secondary metabolites. The conspicuous lack of secondary metabolites in humans and other groups of advanced vertebrates is ascribed to the presence of an advanced immune system. Physical barriers, e.g. skin, chemical barriers, e.g. antimicrobial proteins, or cells that attack foreign cells and body cells harboring infectious diseases confer to non-specific innate immunity. Specialized white blood cells, lymphocytes, help to eliminate foreign molecules (antigens). Invertebrate animals, e.g. insects, have already acquired the ability to produce cells that engulf and destroy foreign material. However, distinct lymphocytes and the production of immunoglobulins (antibodies) are restricted to terrestrial vertebrates. The conspicuous tendency to accumulate secondary metabolites that shows in those organisms that lack a sophisticated immune system thus strongly suggests that secondary metabolites are essential for plant defense against predators, such as viruses, bacteria, fungi, protozooans, worms, and insects. In this context, secondary metabolites are called allelochemicals. However, not all compounds may be exclusively advantageous to the producer (allomones). In some cases, compounds produced by one organism are signals for another organism, e.g. secondary metabolites of a plant can turn into a stimulant for a herbivore insect to locate its host plant and oviposit its eggs on its leaves, and the hatched larvae may sequester plant produced compounds to use them as precursors for their own defense (kairomones).

The term allelopathy was coined in the 40ies of the last century by the Austrian plant physiologist Hans Molisch, who investigated the effects caused by volatile emissions of various fruits (today we know it to be ethylene), such as apple, pears etc., on the development of pea seedlings. He originally defined allelopathy as a chemical plant–plant interaction. Today, allelopathy is more understood to comprise a broad range of interactions in the rhizosphere including those that involve microorganisms as well. The homepage of the International Society of Chemical Ecology (*http://www.chemecol.org*) regards allelopathy as one of its sub-disciplines and defines it rather broadly, as follows: "Allelopathy involves chemical interactions at all levels of complexity, from microorganisms to higher plants, and is inextricably interwoven into ecological phenomena. In this context, competition for food and living space is often carried out chemically: all sorts of antibiotics, toxins, germination- and growth-inhibitors, or stimulants may be released for these purposes. Adsorbed by the surrounding soil or upon direct action through the air, allelochemicals are used by plants and microorganisms to manipulate partners, competitors, and ecosystems. Knowledge of the chemistry and biology of allelochemicals provides many opportunities for practical application in biological control methods." Furthermore, allelopathic interactions are not restricted to terrestrial organisms: "Chemical communication for the peaceable exchange of information as well as for chemical aggression and defense is by no means restricted to the terrestrial world: pheromones and allelochemicals are well known from fish, marine invertebrates, and algae. The co-existence of immobile organisms such as corals or sponges in complex communities is mediated chemically to a large extent, their defense systems being made up of highly active allelochemicals. Some of these compounds exhibit exciting physiological properties that are of high medical and agrochemical interest. Mechanisms of adaptation, including tolerance and symbiosis, feeding preferences, and chemical mimicry are all among the basic aspects of co-evolution which are currently subjects of detailed study".

Originally, the deleterious effects of bark beetles on pine trees have stimulated the interest in the chemical communication of those bark beetles. Pine trees accumulate large amounts of resin as chemical protection and bark beetles were found to sequester monoterpenes from this resin and use them as signal compounds. As a consequence, the discipline of chemical ecology developed that focused the function of secondary metabolite in chemical communications of insects. A good portion of these studies was also directed to plant–herbivore interactions. In this context, the role of plant secondary metabolites as defense agents was explored and the obtained insights revealed that specialized herbivores have developed means to either tolerate, detoxify, or sequester them as precursors for their own chemical defense. In plant physiology, for a long time more attention was paid to abiotic stress, such as temperature, UV light or low nutrient levels. Only recently, biotic stress has been acknowledged as a sub-discipline. In the 2002 edition of "Strasburger's Textbook of Botany", one of the most widespread teaching books of botany in the German speaking countries of Europe, Elmar W. Weiler, in his treatment of plant physiology, divides plant physiology into metabolic physiology, developmental physiology, physiology of movements, and allelophysiology, the latter dealing with the biotic stress of plants.

2. Primary and Secondary Metabolites

First of all, a more elaborate definition and comparison of primary and secondary metabolites of living organisms is necessary: At the end of the 19th century, Albrecht Kossel, a German plant physiologist, opined that plant cells also contain constituents with no obvious function and thus only secondary relevance for the producing organisms. The term ”secondary” then established itself in the major textbooks during the first half of the 20th century including all metabolites that had no function in primary metabolism. Primary metabolism comprises the formation and breakdown of nucleic acids, proteins and their precursors, of certain carbohydrates and carboxylic acids, i.e. essential reactions occurring in all living organisms. The epithet “secondary” is more or less unfortunate, because it implies that such metabolites may be of no value to the producing organism and some researches even opined that secondary metabolites might be waste or shunt products of the plant. However, this erroneous suggestion has never been convincingly corroborated by any experimental evidence. Instead, in a more evolutionary context, numerous studies convincingly suggested that secondary metabolites essentially contribute as allelochemicals to the survival of the producing organism in its environment.



5 .. arginine **6** .. canavanine **7** .. canaline

Figure 2. The nonprotein amino acid canavanine (6) occurs in legume seeds. The aminoacyl-tRNA-synthase of an animal cannot differentiate between arginine (5) and canavanine (6), contrary to that of the plant, and converts canavanine (6) into the neurotoxic amino acid canalin (7).

Today we also know that the distinction into primary and secondary metabolites may be ambiguous. An often-referred-to example represents the amino acid canavanine that occurs in legume seeds. By mimicking the essential amino acid arginine, canavanine becomes toxic to herbivores (a typical function of a secondary metabolite). The aminoacyl-tRNA-synthase of an animal cannot differentiate between arginine (5, Figure 2) and canavanine (6, Figure 2), contrary to that of the plant, and converts canavanine into the neurotoxic amino acid canalin (7, Figure 2). In the plant, the levels of canavanine are especially high in the seeds. However, during germination, canavanine is metabolized and the bound nitrogen is again made available to the growing seedling as nutrient (a function of a primary metabolite). Consequently, distinctions into primary and secondary metabolites should be carried out on basis of the function of the respective metabolite and not only by its chemical structure. Primary and secondary metabolites occur in all living organisms. However, plants accumulate them in considerable amounts in their tissues and this is explains probably why they raised our attention in the first place.

3. Biological Activity

A fundamental condition of the phenomenon of secondary metabolites conferring protection to the producing organism is the so-called biological activity of the chemical. This is also exactly the point where the complexity of the scenario increases. Concomitantly, due to the sheer diversity of structures of secondary metabolites, our knowledge of how a specific secondary metabolite may act decreases. In the ongoing text, two major modes of actions will be outlined: binding to a receptor and interfering with reactive oxygen species (ROS) concentrations.

One fundamental and often referred to characteristic of low molecular weight metabolites of living organisms is that they can bind to macromolecules such as proteins. If the protein is an enzyme, this can fundamentally affect its catalytic function — in the extreme, the enzyme is totally inhibited. However, there exist two major constraints for such a process: (1) the three-dimensional shape of the small molecule has to fit into the pocket of the enzyme like a key into its lock; and (2) the active molecule must somehow travel to its site of action in large enough numbers. During this passage, intact membranes represent major barriers that block many compounds apart from those of a more lipophilic nature. Not surprisingly, many bioactive secondary metabolites are also lipophilic, and thus may diffuse through membranes and then bind to transcription factors or interact with intracellular signal cascades. Targets on the cell surface include ion channels, such as for calcium and potassium, catalytic receptors of transmembranic enzymes, such as tyrosine-specific protein kinases, or receptors of G proteins. As a consequence, biological activity is more or less a rather rare phenomenon. The low hit rates in pharmaceutical screening studies, which, by the majority, are receptor-binding assays, reflect this fact. Consequently, Richard Firn and Clive G. Jones developed the "screening hypothesis", which rates the numerous tentatively inactive secondary metabolites as important pool for precursors for the evolution of active compounds and thus offers an explanation for secondary metabolite diversity. In respect to efficient plant defense, the question is if such a mode of action is really efficient enough to act as universal principle. Actually, there will always be plant species that contain secondary metabolites with demonstrable biological activities, but at the same time, they will co-exist with other species that are similarly successful and lack this specific defense compound. Another argument that may be especially applied to plants is that the high amounts of accumulated secondary metabolites work as an efficient defense just through their high concentrations.

Besides binding to receptor pockets of proteins, the possibility of interacting with signal cascades represents an alternative mode of action. Naturally, this can be achieved by binding to receptors, but in case of reactive oxygen species (ROS) secondary metabolites are capable of interfering with the concentration of the signal molecule itself. On one hand, especially in higher concentrations, reactive oxygen species are highly poisonous and may lead to cell death; on the other hand, both plant and animal cells have developed mechanisms that keep ROS concentration low enough to serve as a multifaceted signal molecule.

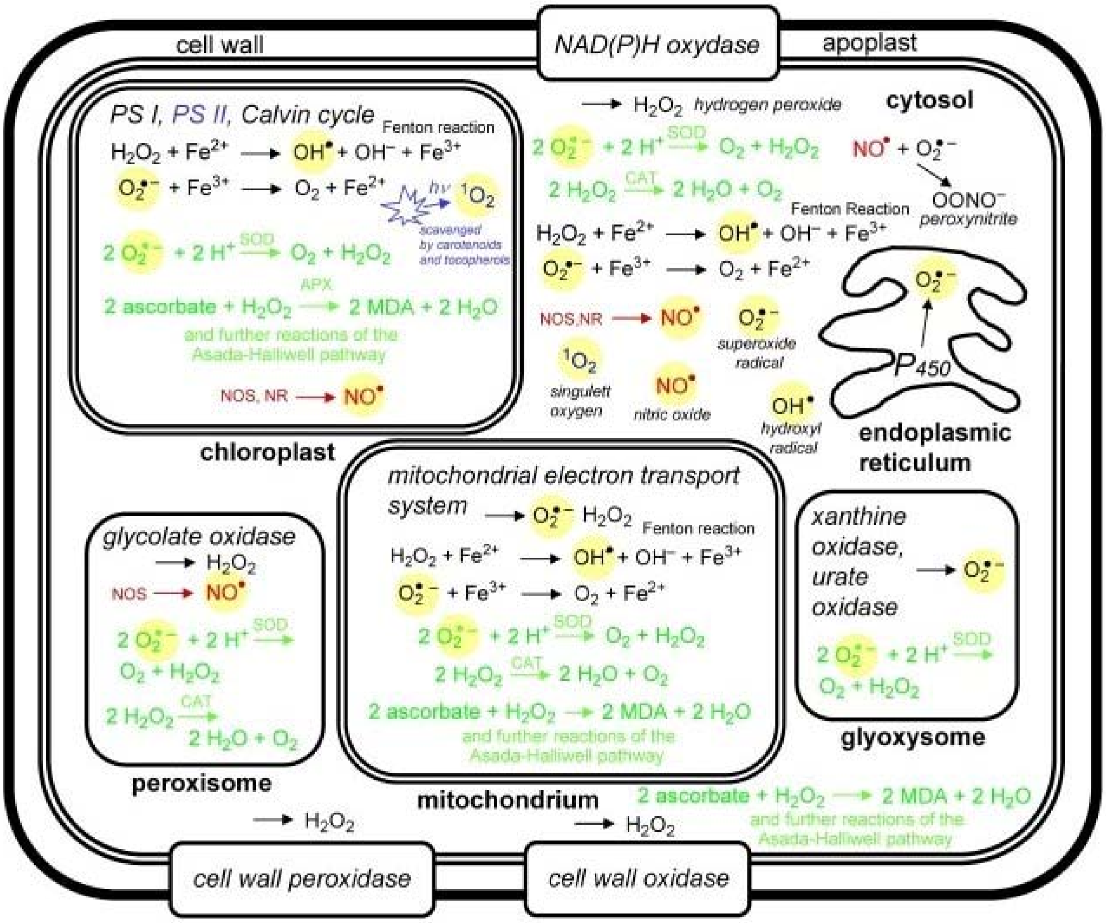


Figure 3. A selection of source and protection mechanisms of and against reactive oxygen species (ROS) in plants; hydrogen peroxide, singlet oxygen, superoxide, anion, hydroxyl radical, and nitric oxide; radicals are marked in yellow; APX, ascorbate peroxidase; CAT, catalase; MDA, mondehydroascorbate; NR, nitrate reductase; NOS, nitric oxide synthase, utilizing L-arginine as substrate; P450, P450 multifunctional monooxygenase; SOD, superoxide dismutase; the detoxification of hydrogen peroxide, the Asada-Halliwell pathway is not completely shown due to space limitations.

During the evolution of organisms that are adapted to aerobic conditions, the production of ROS is an unavoidable consequence of metabolic processes, such as respiration and photosynthesis, and has necessitated the evolution of ROS scavengers in order to minimize the cytotoxic effects of ROS in the cell. Concomitantly, sensing changes of ROS concentrations that result from metabolic disturbances allows plants to activate responses that help in dealing with abiotic and biotic stress. Figure 3 presents an overview of reactions in the single organelles of a plant cell that either lead to the formation or the quenching of reactive oxygen species, in particular hydrogen peroxide (H_2O_2), superoxide radical ($O_2^{\bullet-}$), and hydroxyl radical ($OH^\bullet$). Recently, nitric oxide ($NO^\bullet$) was also discovered to constitute an extracellular messenger. Together with the hormones jasmonic and salicylic acid¸ ROS and nitric oxide are today recognized as intra- and extracellular signal compounds of the plant cell in context with resistance against microbial pathogens and herbivores. Furthermore, the intensive exploration of potential functions of these chemicals as signal molecules has revealed that nitric oxide and ROS are involved in various responses against biotic and abiotic stress factors that are summarized in Figure 4. ROS and nitric oxide activate mitogen-activiated protein kinases (MAPK), protein phosphatases, and transcription factors. By this mode of action, they can induce expression of hitherto silent genes.

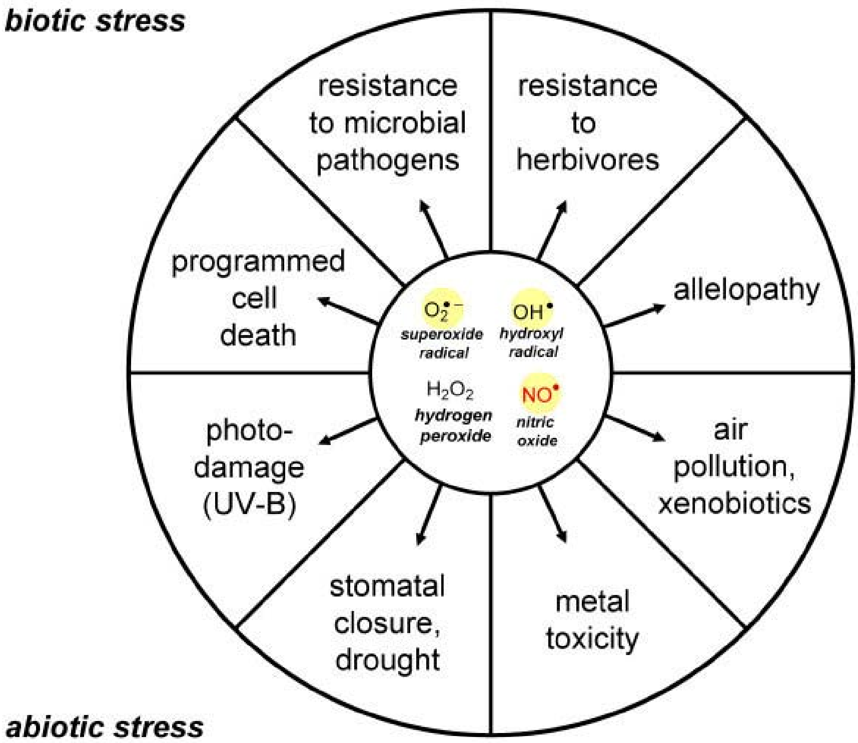
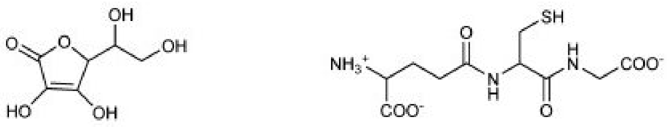


Figure 4. Currently known biotic and abiotic stresses in the course of which ROS and nitric oxide are known to act as signal molecules.

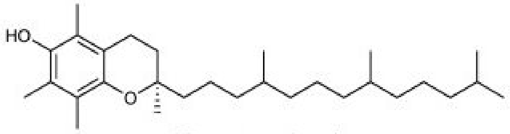
Plant cells are also known to contain various antioxidants that help to control the concentrations of ROS including ascorbate (8, Figure 5), glutathione (9, Figure 5), α-tocopherol (10, Figure 5), β-carotene (11, Figure 5) and zeaxanthin (12, Figure 5). Flavonoids and phenols - for examples note the structures of the stilbene resveratrol (13, Figure 5) and the flavonoid quercetin (14, Figure 5) - may scavenge ROS and also chelate iron; both properties can contribute to protect against ROS formation; Fe^{2+} is also involved in the formation of hydroxyl radicals. Conversely, especially herbicides, such as paraquat, are again known to generate ROS. Cercosporin (15, Figure 5), a fungal toxin, reacts after light activation with oxygen to form superoxide radicals, which cause severe lipid peroxidation. This exemplifies that phenolic secondary metabolites (Ph) may potentially interfere with regulatory mechanisms of ROS concentrations in cells in both ways.

$$\text{Ph-O}^{\bullet -} + O_2 \rightarrow \text{Ph=O} + O_2^{\bullet -}$$

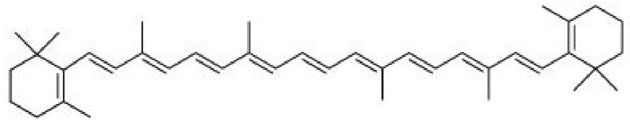
$$\text{Ph-OH} + O_2^{\bullet -} + H^+ \rightarrow \text{Ph-O}^{\bullet -} + H_2O_2$$



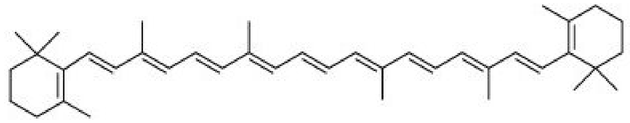
8 .. ascorbate **9** .. glutathione



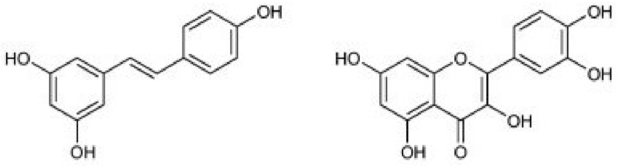
10 .. α-tocopherol



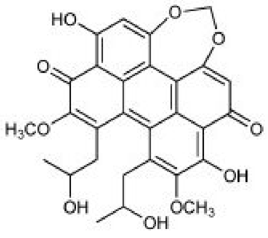
11 .. β-carotene



12 .. zeaxanthine



13 .. resveratrol **14** .. quercetin



15 .. cercosporin

Figure 5. Structures of radical scavengers, ascorbate (8), glutathione (9), α-tocopherol (10), β-carotene (11) and zeaxanthin (12), resveratrol (13), quercetin (14), and the superoxide anion forming cercosporin (15).

In addition, some phenolic secondary metabolites are prone to autooxidation:

$$\text{Ph-OH} + O_2 \rightarrow \text{Ph-O}^{\bullet-} + O_2^{\bullet-} + H^+$$

Further studies are required to explore not only radical-scavenging but also radical-generating properties to obtain more insights into the nature and the extent of the specific effects secondary metabolites may exert on the regulatory mechanisms of ROS in the cell.

-
-
-

Bibliography

Apel K., Hirt H. (2004) Reactive oxygen species: metabolism, oxidative stress, and signal transduction. *Annual Reviews of Plant Biology* 55, 373–399. [This reviews the function of reactive oxygen species, such as superoxide anion and hydroxyl radical, as intra- and intercellular signal molecules and activators of mitogen-activated protein kinases].

Bever J. (2003) Soil community feedback and the coexistence of competitors: conceptual frameworks and empirical tests. *New Phytologist* 157, 465–473. [This describes a model that uses positive and negative feedbacks of the soil microbial community as factor to explain species composition in old field communities; it explains why negative feedbacks facilitate the coexistence of species].

Callaway R.M., Ridenour W.M. (2004) Novel weapons: invasive success and the evolution of increased competitive ability. *Frontiers in the Ecology and Environment* 2, 436–443.

Calvo A.M., Wilson R.A., Bok J.W., Keller N.P. (2002) Relationship between secondary metabolism and fungal development. *Microbiology and Molecular Biology Reviews* 66, 447–459. [This reviews the linkages between morphological differentiation and the biosynthesis of secondary metabolites in fungi].

Close D.C., McArthur C. (2002) Rethinking the role of many plant phenolics – protection from photodamage not herbivores? *Oikos* 99, 166–172. [This suggests an alternative hypothesis for the evolution of plant phenolic diversity: protection from photodamage].

Czárán T,l., Hoekstra R.F., Pagie L. (2002) Chemical warfare between microbes promotes biodiversity. *Proceedings of the National Academy Of Sciences USA* 99, 786–790. [This provides experimental proof that antibiotic producing bacterial strains facilitate the maintenance of diversity in a community].

Daly J.W., Spande T.F., Garrafo H.M. (2005) Alkaloids from amphibian skin: a tabulation of over eight-hundred compounds. *Journal of Natural Products* 68, 1556–1575. [This reviews the structural diversity, occurrence, and biosynthetic origin of lipophilic alkaloids from amphibian skins].

Dangl J.R., Jones J.D. (2001) Plant pathogens and integrated defence responses to infection. *Nature* 411, 826–833. [This summarizes the current knowledge of molecular mechanisms of plant resistance against pathogens].

Delledone M (2004) NO news is good news for plants. *Current Opinion in Plant Biology* 8, 390–396. [This presents a summary of our currant of nitric oxide as a signal molecule in plant cells].

Dicke M., Takken W. (2006): *Chemical Ecology – From Gene to Ecosystem*, pp. 189. Dordrecht: Springer. [This presents current topics in chemical communications and suggests research avenues to incorporate molecular methodologies into chemical ecology].

Ehrlich P.R., Raven, P.H. (1964) Butterflies and plants: a study in coevolution. *Evolution* 18, 586-608. [This introduces the theory of coevolution between plants and their herbivore predators leading to secondary metabolite diversity and established the notion that plant secondary metabolites have evolved as chemical defense against herbivore predators].

Engel S., Jensen P.R., Fennical W. (2002) Chemical Ecology of marine microbial defense. *Journal of Chemical Ecology* 28, 1971–1985. [This reviews the current knowledge on and methodologies to assess microbial defense properties of secondary metabolites from marine organisms in an ecological context].

Firn R.D., Jones C.G. (2003) Natural products — a simple model to explain chemical diversity. *Natural Products Reports* 20, 382–391. [This outlines the screening hypothesis, which tries to explain the structural diversity in secondary metabolism and why so many secondary metabolites obviously lack any biological activity].

Gershenzon J. (2002) Secondary metabolites and plant defense. *Plant Physiology, 3rd Ed.* (eds. L. Taiz, E. Zeiger), 283–308. Sunderland, Massachusetts, USA: Sinauer Associates. [This provides an introduction to chemical plant defence]

Hadacek F. (2002). Secondary metabolites as plant traits: Current assessment and future perspectives. *Critical Reviews in Plant Sciences* 21, 273–322. [This reviews the recognition of secondary metabolites as plant traits, from markers in taxonomy to mediators of biotic interactions including constitutive and induced defenses].

Harborne J.B. (1993). *Introduction to Ecological Biochemistry,* 384 pp. Oxford, UK: Academic Press. [This is a standard introductory textbook to chemical ecology].

Inderjit, Mallik A.U. (2002) *Chemical Ecology of Plants: Allelopathy in Aquatic and Terrestrial Ecosystems*, pp. 272. Basel: Birkhäuser. [A current overview of alleopathic phenomena].

Janzen D.H. (1977). Why fruits rot, seeds mold, and meat spoils. *The American Naturalist* 111, 691–713. [This explores an ecological function for the production of secondary metabolites of microorganisms].

Langenheim J.H. (2003). *Plant Resins: Chemistry, Evolution, Ecology, Ethnobotany*, pp. 586. Portland, Cambridge: Timber Press. [This presents an exhaustive survey of the biology of plant resins].

Luckner, M. (1990). *Secondary Metabolites in Microorganisms, Plants and Animals*, 3rd ed. 563 pp. Jena: Gustav Fischer. [A basic introduction of biosynthetic pathways to secondary metabolites].

McClintock J.B., Baker B.J. (2002) *Marine Chemical Ecology*. 610 pp. Boca Raton, London: CRC Press. [This reviews chemical defense in marine organisms].

Morgan E.D. (2004): *Biosynthesis in Insects*, 199 pp. Cambridge: The Royal Society of Chemistry.

Nishida R. (2002) Sequetration of defensive substances from plants by Lepidoptera. *Annual Review of Entomology* 47, 57–92. [This reviews the biochemical, physiological, and ecological characteristics of phytochemical-based defense systems in lepidopteran butterflies].

Paul V.J., Puglisi M.P., Ritson-Williams R. (2006) Marine chemical ecology. *Natural Products Reports* 23, 153–180. [This reviews progress in marine chemical ecology between 2003 and 2005].

Perl-Treves R., Perl A. (2002) Oxidative stress: An Introduction. *Oxidative Stress in Plants* (eds D. Inzé, M. Van Montagu), 1–32. London, New York: Taylor & Francis. [This presents an introduction to regulation reactions of reactive oxygen species concentrations in the plant cell].

Piel J. (2004) Metabolites from symbiotic bacteria. *Natural Products Reports* 21, 519–538. [This reviews secondary metabolites that are suspected to be produced by symbiotic bacteria in eukaryotes].

Romeo J.T., Ibrahim R., Varin L. (2000). *Evolution of Metabolic Pathways*. 467 pp. Oxford, UK: Elsevier Science. [Introduction to enzyme families involved in secondary metabolism].

Rosenthal G.A., Berenbaum M.R. (1992) *Herbivores: Their Interactions with Secondary Plant Metabolites,* 493 pp. San Diego: Academic Press. [Various chapters focus on different aspects of interactions between plants and herbivores and explore the function of secondary metabolites in this scenario].

Seigler D.S. (1998) *Plant Secondary Metabolism*. 759 pp. Norwell, USA: Kluwer Academic Publishers. [Recommendable overview of secondary metabolites occurring in plants].

Sitte P., Weiler E.W., Kadereit J.W., Bresinsky A., Körner C. (2002) *Strasburger – Lehrbuch der Botanik*. 1123 pp. Heidelberg, Berlin: Spektrum Akademischer Verlag. [In the chapter on plant physiology, E.W. Weiler introduces allelophysiology, a discipline that focuses on the physiology of biotic interactions of plants].

Stamp N. (2003) Out of the quagmire of plant defense hypotheses. *Quarterly Review of Biology* 78, 23–55. [A critical assessment of existing hypotheses trying to predict mechanisms of plant defense].

Biographical Sketch

Franz Hadacek is associate professor at the Department of Chemical Ecology and Ecosystem Research at the Vienna Ecology Centre of the University of Vienna, Austria. Studies of Botany and Chemistry at the University of Vienna have led to an interest in chemotaxonomy which later changed to a more chemical ecological approach of exploring the functions of secondary metabolites in biotic interactions. Current research aims to understand secondary metabolite-mediated processes in the rhizosphere and on leaf surfaces.