CHEMISTRY OF NATURAL PRODUCTS

J. M. E. Quirke
Department of Chemistry and Biochemistry and Center for Ethnobiology and Natural Products, Florida International University, Miami, FL 33199 USA

B. C. Bennett
Department of Biological Sciences and Center for Ethnobiology and Natural Products, Florida International University, Miami, FL 33199 USA

Keywords : acetyl coenzyme A, alkaloid pathway, amino acid, anthocyanin, biosyntheses, cardioactive sterol glycoside, carotenoid, coumarin, deoxyxylulose, diterpene, erythrose-4- phosphate, flavonoid, gallic acid, isopentenyl pyrophosphate, isoprene, isoprenoidal pathway, lignan, lignin, medicinal plants, methylxanthine alkaloid, mevalonic acid, natural products, phenolic, plant secondary metabolites, polyketide pathway, purine alkaloid, pyrrolizidine alkaloid, resveratrol, salicylic acid, saponin, sesquiterpene, shikimic acid pathway, sterol, stilbene, tannin, terpenoid, triterpenes

Contents

1. Introduction
2. Secondary Metabolism and Natural Products
3. Polyketide Pathway
3.1. Arachidonic Acid
3.2. Aflatoxin
3.3. Identification of Polyketide Metabolites
4. Isoprenoidal Pathway
4.1. Terpenoids
4.2. Classes of Terpenoids
4.3. Six-membered ring monoterpenes
4.4. Iridoids
4.5. Irregular Monoterpenes
4.6. Sesquiterpenes
4.7. Diterpenes
4.8. Triterpenes: Sterols
4.8.1. Saponins
4.9. Tetraterpenes
5. Shikimic Acid Pathway
5.1. Gallic Acid and Tannins
5.2. Chorismic Acid
5.2.1. Anthranilic Acid, Tryptophan, Salicylic Acid and Para-aminobenzoic Acid
5.2.2. Phenylalanine and Tyrosine
5.2.3. Aromatic Propenoic Acids
5.2.4. Lignins
5.2.5. Lignans
5.2.6. Coumarins
6. Mixed Pathways

6.1. Stilbene – Resveratrol
6.2. Flavonoids and Anthocyanins
6.3. Terpenoid Quinones
7. Alkaloid Pathway
7.1. Ornithine Derivatives
7.2. Putrescine Derivatives
7.3. Lysine Derivatives
7.4. Nicotinic Acid Derivatives
7.5. Phenylalanine and Tyrosine Derivatives
7.5.1. Dopamine
7.5.2. Opiate Alkaloids
7.6. Trytophan Derivatives
7.6.1. Tryptamine and Secologanin Derivatives
7.6.2. Tryptophan and Isoprene Derivatives
7.7. Penicillins
7.8. Purine Derivatives
8. Conclusions
Glossary
Bibliography
Biographical Sketches

Summary

Four secondary metabolic pathways (polyketide, isoprenoidal, shikimic acid, and alkaloid) produce an amazing diversity of natural products in living organisms, especially in plants. These natural products are essential for human existence. Here, we discuss examples of important compounds produced by each of the four pathways, as well as compounds that derive from mixed pathways. Our aim is not to provide an exhaustive survey of each pathway and its derived products. Rather, our goal is to outline these pathways and to show how slight modifications in pathways generate the astounding diversity of natural products. For many of these compounds, the complexity of syntheses in a single cell cannot be duplicated in the most sophisticated laboratory. For each of the natural products discussed, we provide examples of plants, fungi, or bacteria that produce them. We also provide a complete set of common names, binomials with author citations, relevant synonyms, and families for all organisms discussed in the text. The abundant figures are color coded to help show which part of each compound is derived from which pathway.

1. Introduction

Plants provide a plethora of natural products that are essential for human survival. For much of the world's population, the botanical kingdom supplies most medicines, resins, latex, gums, dyes, poisons, and fragrances (Figure 1). Even the most highly industrialized cultures rely on chemical compounds manufactured by plants. In this chapter, we provide a broad overview of plant natural products and their biosynthetic pathways. We describe the four principle secondary metabolic pathways – polyketide, isoprenoidal (including mevalonic acid), shikimic acid, and alkaloid. Examples of secondary metabolites that are formed by a combination of pathways also are examined.

Our objective is to show how the four principle biosynthetic pathways produce an astonishing diversity of botanical and fungal compounds.

Figure 1. Chinese medicinal plant shop in San Franciso, CA (USA).

2. Secondary Metabolism and Natural Products

Before starting these discussions, it is necessary to define primary and secondary metabolites. Primary metabolites are compounds that are essential for life and found across broad taxonomic categories. They include DNA, protein amino acids, and chlorophyll. The so-called “secondary” metabolites were originally defined as natural products that had no known function. They now are considered to be compounds that have a limited taxonomic distribution. Secondary metabolites may not be necessary for every species, but that does not diminish their importance. Flower petals would be ineffective pollinator attractors without anthocyanins and other floral pigments. Herbivores would overwhelm plants that lacked defensive compounds such as tannins and alkaloids. The term secondary is misleading because it implies that the importance of these compounds is less than that of primary compounds. Moreover, the biosynthesis of many plant constituents is complex, employing both primary and secondary metabolic pathways. Many, as do we, prefer the term “plant natural products” instead of secondary metabolites.

The source of carbon for both primary and secondary metabolites is carbon dioxide and the process that links all these compounds directly or indirectly is photosynthesis (Figure 2). Each of the four secondary metabolic pathways uses the acetate ion ($CH_3CO_2^-$) as a direct or indirect starting material. Acetate plays a central role in both the photosynthetic pathway where carbon dioxide is transformed into glucose (three acetate molecules are converted into one glucose molecule) and in the glycolytic and citric acid cycles where glucose is degraded to three molecules of acetate. These three molecules are then decomposed to six CO_2 molecules.

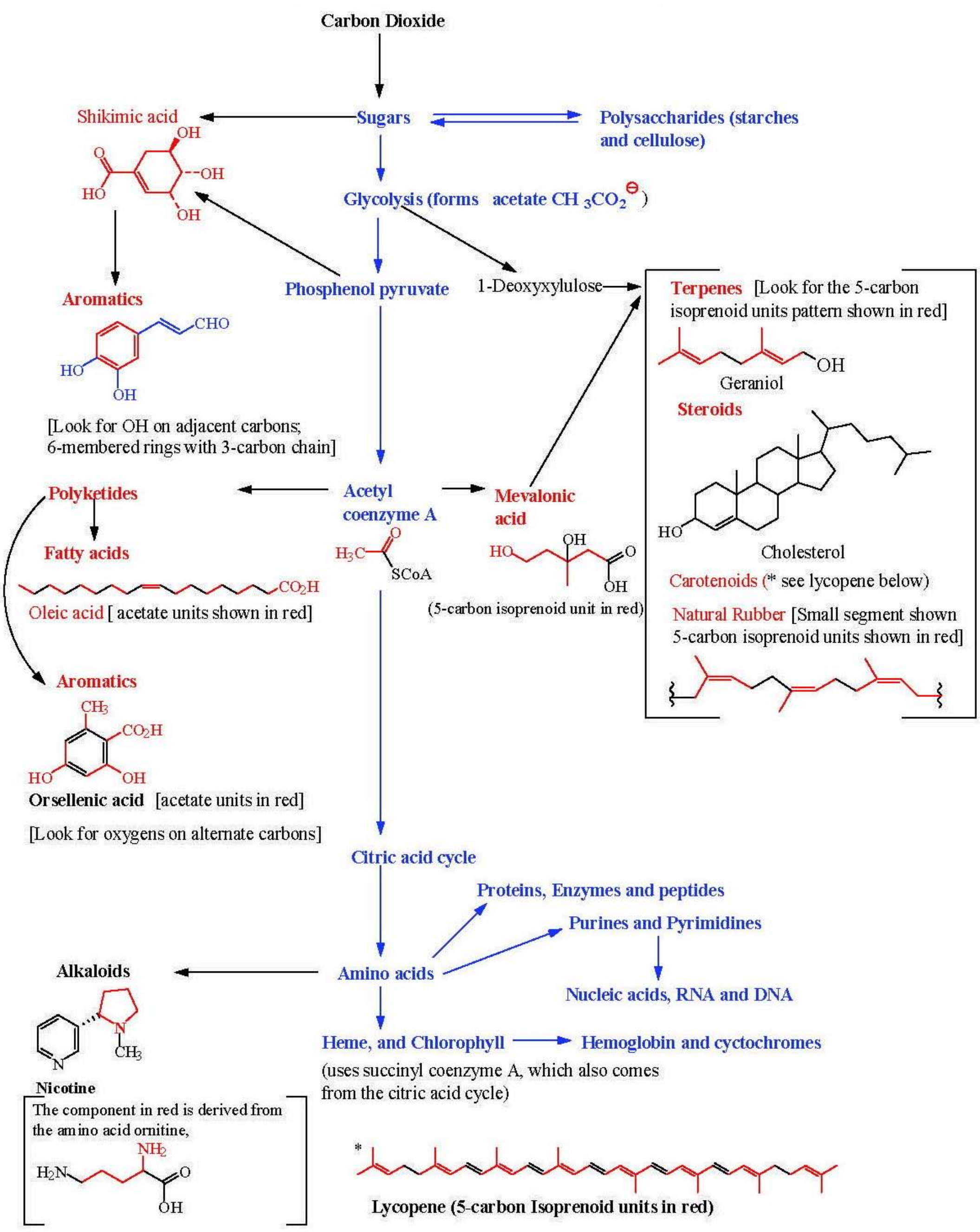

Figure 2. Summary of the pathways from carbon dioxide and photosynthesis to important classes of primary and secondary metabolites. Primary metabolites and pathways to primary metabolites are indicated by blue arrows and blue font. Secondary metabolic pathways are indicated by black arrows. Secondary metabolites are drawn in red or red and black, when it is possible to identify the units of the starting material (the isoprenoid units for isoprenoidal secondary metabolites, the acetate carbons for polyketide metabolites, the aromatic ring for shikimic acid metabolites, and the amino acid components of alkaloids).

3. Polyketide Pathway

Polyketides are made by combining several (usually 10 or fewer) acetate units to form a chain that can undergo a variety of reactions. Acetyl CoA (acetyl CoA = $CH_3COSCoA$), is nature's building block for introducing two carbon units into molecules. Polyketide biosynthesis starts with the acetate in its more reactive form, acetyl coenzyme A (Figure 3). This compound, a member of the thioester family (with general formula, $RCOSR^1$), is more reactive than ordinary esters.

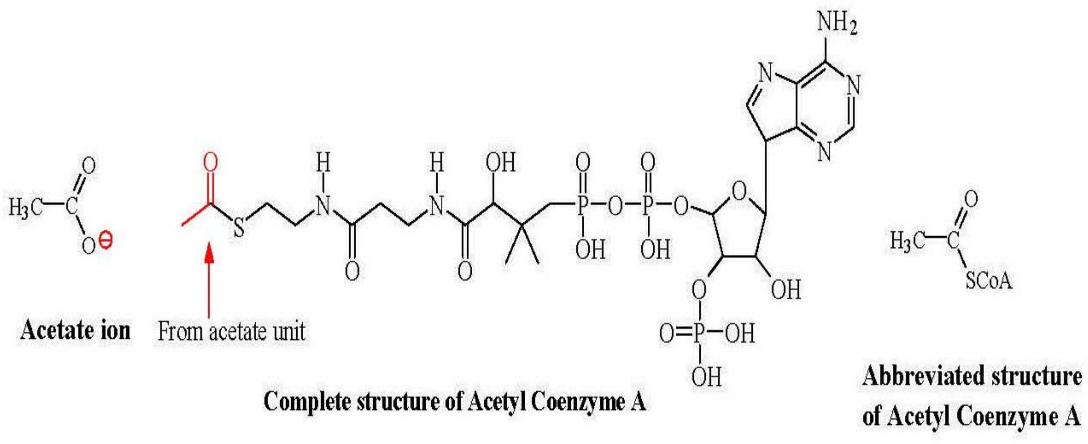

Figure 3. Structure of acetyl coenzyme A.

Acetyl CoA is further activated by the temporary incorporation of a carbon dioxide unit, a process accompanied by replacement of the SCoA group with sulfur-linked proteins. The product links with other molecules of acetyl CoA (or compounds of the form CH_3COSX, in which the SCoA unit is replaced by other sulfur linked groups). Polyketide biosyntheses typically lead to either fatty acids and related straight-chain compounds or aromatic compounds. The major difference between the pathways to the two compounds classes is that the oxygen of the carbonyl unit ($C=O$) is almost immediately removed during the linking of the acetyl coenzyme A units in fatty acid biosyntheses. It usually is retained when the acetate units link to form aromatic compounds.The formation of tetradecanoic acid or myristic acid (a common fatty acid named after *Myristica*, the genus of nutmeg) exemplifies the fatty acid pathway (common names, binomials with author citations, and family names for all plant and fungal species cited in the text can be found in Appendix 1). Seven acetic acid units link together to form this compound (Figure 4). Biosynthesis of 6-methyl salicylic acid, illustrates the route to aromatic compounds. Only one of the carbonyl units ($C=O$) is reduced to an alcohol and dehydrated, before the ring is formed. 6-Methyl salicylic acid occurs in the fungus *Penicillium solitum* var. *solitum*, which is a common contaminant of apples. The 6-methyl salicylic acid undergoes a complex set of reactions, including ring opening, rearrangements, oxidations, loss of the carboxylic acid, and introduction of another carboxylic acid group to form the carcinogen, patulin. Foodstuffs are routinely screened for patulin, which may not exceed a concentration of 50 μg/kg.

Common name	Binomial	Family
Aloe	*Aloe vera* (L.) Burm. f.	Asphodelaceae
American ginseng	*Panax quinquefolius* L	Araliaceae
Amirucu	*Psychotria viridis* Ruiz & Pav.	Rubiaceae
Angel's trumpet	*Brugmansia suaveolens* (Humb. &	Solanaceae

	Bonpl. ex Willd.) Bercht. & J. Presl	
Anise	*Pimpinella anisum* L.	Apiaceae
Anthrax bacterium	*Bacillus anthracis* Cohn	Bacillaceae
Arracacha	*Arracacia xanthorrhiza* Bancr.	Apiaceae
Aspergillus	*Aspergillus flavus* Link	Trichocomaceae
Aspergillus	*Aspergillus parasiticus* Speare	Trichocomaceae
Ayahusaca	*Banisteriopsis caapi* (Spruce ex Griseb.) C. V. Morton	Malpighiaceae
Bakanae fungus	*Gibberella fujikuroi* (Sawada) Wollenw.	Nectriaceae
Balsam fir	*Abies balsamea* (L.) Mill.	Pinaceae
Balsam poplar	*Populus balsamifera* L.	Salicaceae
Barley	*Hordeum vulgare* L.	Poaceae
Bishop’s weed	*Ammi majus* L.	Apiaceae
Black birch	*Betula lenta* L.	Betulaceae
Black pepper	*Piper nigrum* L.	Piperaceae
Blue gum	*Eucalyptus globulus* Labill.	Myrtaceae
Bog bean	*Menyanthes trifoliata* L.	Menyanthaceae
Borneo camphor	*Dryobalanops aromatica* C. F. Gaertn.	Dipterocarpaceae
Brewers yeast	*Saccharomyces cerevisiae* Meyen ex E.C. Hansen	Saccharomycetaceae
Cacao	*Theobroma cacao* L.	Malvaceae
Camphor tree	*Cinnamomum camphora* (L.) J. Presl	Lauraceae
Canela	*Ocotea quixos (Lam.) Kosterm*.	Lauraceae
Cardamom	*Elettaria cardamomum* (L.) Maton	Zingiberaceae
Carrot	*Daucus carota* L. subsp. *sativus* (Hoffm.) Arcang.	Apiaceae
Celery	*Apium graveolens* L.	Apiaceae
Chinese ginseng	*Panax ginseng* C. A. Mey.	Araliaceae
Chinese red pine	*Pinus massoniana* Lamb.	Pinaceae
Cinnamon	*Cinnamomum verum* J. Presl	Lauraceae
Citronella	*Cymbopogon nardus* (L.) Rendle	Poaceae
Clove oil	*Syzygium aromaticum* (L.) Merr. & L. M. Perry	Myrtaceae
Coca	*Erythroxylum coca* Lam.	Erythroxylaceae
Coffee	*Coffea arabica* L.	Rubiaceae
Cola nut	*Cola acuminata* (P. Beauv.) Schott & Endl.	Malvaceae
Cola nut	*Cola nitida* (Vent.) Schott & Endl.	Malvaceae
Comfrey	*Symphytum officinale* L.	Boraginaceae
Common foxglove	*Digitalis purpurea* L.	Plantaginaceae

Common groundsel	*Senecio vulgaris* L.	Asteracae
Common liverwort	*Marchantia polymorpha* L.	Marchantiaceae
Corn	*Zea mays* L.	Poaceae
Crescent-cup liverwort	*Lunularia cruciata* (L.) Dumortier	Lunulariaceae
Cucumber	*Cucumis sativus* L.	Cucurbitaceae
Damask rose	*Rosa* × *damascena* Mill.	Rosaceae
Deadly nightshade	*Atropa belladonna* L.	Solanaceae
Dog fennel	*Eupatorium capillifolium* (Lam.) Small	Asteraceae
Eastern hemlock	*Tsuga canadensis* (L.) Carrière	Pinaceae
English walnut	*Juglans regia* L.	Juglandaceae
Ephedra	*Ephedra sinica* Stapf	Ephedraceae
Ergot	*Claviceps purpurea* (Fr.) Tul.	Clavicipitaceae
European chestnut	*Castanea sativa* Mill.	Fagaceae
European pennyroyal	*Mentha pulegium* L.	Lamiaceae
European yew	*Taxus baccata* L.	Taxaceae
Feverfew	*Tanacetum parthenium* (L.) Sch. Bip.	Asteraceae
Field mint	*Mentha arvensis* L.	Lamiaceae
Flax	*Linum usitatissimum* L.	Linaceae
Fly agaric	*Amanita muscaria* (L.) Lam.	Amanitiaceae
Garden angelica	*Angelica archangelica* L.	Apiaceae
Garlic	*Allium sativum* L.	Alliaceae
Ginger	*Zingiber officinale* Roscoe	Zingiberaceae
Ginkgo	*Ginkgo biloba* L.	Ginkgoaceae
Golden ragwort	*Packera glabella* (Poir.) C. Jeffrey	Asteraceae
Grape	*Vitis vinifera* L.	Vitaceae
Grapefruit	*Citrus* x *paradisi* Macfad.	Rutaceae
Grecian foxglove	*Digitalis lanata* Ehrh.	Plantaginaceae
Henbane	*Hyoscyamus niger* L.	Solanaceae
Himalayan mayapple	*Podophyllum hexandrum* Royle	Berberidaceae
Hops	*Humulus lupulus* L.	Cannabaceae
House geranium	*Pelargonium* ×*hortorum* L. H. Bailey	Geraniaceae
Hybrid rose	*Rosa dilecta* Rehder	Rosaceae
Indian snakeroot	*Rauvolfia serpentina* (L.) Benth. ex Kurz	Apocynaceae
Japanese knotweed	*Fallopia japonica* (Houtt.) Ronse Decr.	Polygonaceae
Japanese star anise	*Illicium anisatum* L.	Illiaceae
Jimsonweed	*Datura stramonium* L.	Solanaceae
Kale	*Brassica oleracea* L. var. *viridis* L.	Brassicaceae
Kudzu	*Pueraria montana* (Lour.) Merr. var.	Fabaceae

	lobata (Willd.) Maesen & S. M. Almeid ex Sanjappa & Predeep	
Lemon	*Citrus limon* (L.) Burm. f.	Rutaceae
Madagascar periwinkle	*Catharanthus roseus* (L.) G. Don	Apocynaceae
Mandrake	*Mandragora officinarum* L.	Solanaceae
Marijuana	*Cannabis sativa* L. subsp. *indica* (Lam.) E. Small & Cronquist	Cannabaceae
Mayapple	*Podophyllum peltatum* L.	Berberidaceae
Meadowsweet	*Filipendula ulmaria* (L.) Maxim. [syn.: *Spiraea ulmaria* L.]	Rosaceae
Mexican yam	*Dioscorea mexicana* Scheidw.	Dioscoreaceae
Mold	*Penicillium chrysogenum* Thom [syn. *Penicillium notatum* Westling	Trichomaceae
Mold	*Penicillium expansum* Link [syn. *Penicillium glaucum* Stoll]	Trichocomaceae
Mold	*Penicillium griseofulvum* Dierckx	Trichocomaceae
Mold	*Penicillium solitum* var. *solitum* Westling[syn. *Penicillium patulum* Bainier]	Trichocomaceae
Nutmeg	*Myristica fragrans* Houtt.	Myristicaceae
Opium poppy	*Papaver somniferum* L.	Papaveraceae
Pacific yew	*Taxus brevifolia* Nutt.	Taxaceae
Para rubber	*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.	Euphorbiaceae
Partridge berry	*Gaultheria procumbens* L.	Ericaceae
Pecan	*Carya illinoinensis* (Wangenh.) K. Koch	Juglandaceae
Peppermint	*Mentha* × *piperita* L.	Lamiaceae
Peyote	*Lophophora williamsii* (Lem. ex Salm-Dyck) J. M. Coult.	Cactaceae
Pigweed	*Amaranthus hybridus* L.	Amaranthaceae
Pituri	*Duboisia myoporoides* R. Br.	Solanaceae
Poison hemlock	*Conium maculatum* L.	Apiaceae
Prince’s feathers	*Amaranthus hypochondriacus* L.	Amaranthaceae
Pumpkin seed	*Cucurbita pepo* L.	Cucurbitaceae
Pygeum	*Prunus africana* (Hook. f.) Kalkman	Rosaceae
Pyrethrum	*Tanacetum cinerariifolium* (Trevir.) Sch. Bip. [syn.: *Chrysanthemum cinerariifolium* (Trevir.) Vis.]	Asteraceae
Pyrethrum	*Tanacetum coccineum* (Willd.) Grierson[syn.: *Chrysanthemum coccineum* Willd.]	Asteraceae
Quebracho	*Schinopsis quebracho-colorado*	Anacardiaceae

	(Schltdl.) F. A. Barkley & T. Mey.	
Red mangrove	*Rhizophora mangle* L.	Rhizophoraceae
Rose geranium	*Pelargonium graveolens* L'Hér.	Gernaiaceae
Rye	*Secale cereale* L.	Poaceae
San pedro	*Echinopsis pachanoi* (Britton & Rose) Friedrich & G. D. Rowley	Cactaceae
Sarsaparilla	*Smilax regelii* Killip & C. V. Morton	Smilacaceae
Saw palmetto	*Serenoa repens* (W. Bartram) Small	Arecaceae
Scarlet milkweed	*Asclepias curassavica* L.	Apocynaceae
Scurfy pea	*Cullen corylifolium* (L.) Medik. [syn.: *Psoralea corylifolia* L]	Fabaceae
Seaside heliotrope	*Heliotropium curassavicum* L.	Boraginaceae
Sesame seed	*Sesamum indicum* L.	Pedaliaceae
Shikimi	*Illicium anisatum* L.	Illiaceae
Showy rattlebox	*Crotalaria spectabilis* Roth	Fabaceae
Siberian ginseng	*Eleutherococcus senticosus* (Rupr. & Maxim.) Maxim.	Araliaceae
Slash pine	*Pinus elliottii* Engelm.	Pinaceae
Snowberry	*Symphoricarpos albus* (L.) S. F. Blake	Caprifoliaceae
Sour orange	*Citrus aurantium* L.	Rutaceae
Soy bean	*Glycine max* (L.) Merr.	Fabaceae
Spinach	*Spinacia oleracea* L.	Amaranthaceae
Streptomycete	*Streptomyces hygroscopicus* (Jensen) Waksman & Henrici	Streptomycetaceae
Strychnine tree	*Strychnos nux-vomica* L.	Loganiaceae
Sugar maple	*Acer saccharum* Marshall	Sapindaceae
Sunflower seed	*Helianthus annuus* L.	Asteraceae
Sweet clover	*Melilotus albus* Medik.	Fabaceae
Sweet clover	*Melilotus officinalis* (L.) Lam.	Fabaceae
Sweet orange	*Citrus sinensis* (L.) Osbeck	Rutaceae
Syrian rue	*Peganum harmala* L.	Nitrariaceae
Tea tree	*Melaleuca alternifolia* (Maiden & Betche) Cheel	Myrtaceae
Tea	*Camellia sinensis* (L.) Kuntze	Theaceae
Thompson seedless grape	*Vitis vinifera* L.	Vitaceae
Tobacco	*Nicotiana tabacum* L.	Solanaceae
Tomato	*Solanum lycopersicum* L.	Solanaceae
Typhoid bacterium	*Salmonella enterica* Le Minor and Popoff serovar Typhi	Enterobacteriaceae
Vanilla	*Vanilla planifolia* Andrews	Orchidaceae
Velvet bean	*Mucuna pruriens* (L.) DC	Fabaceae

Wheat	*Triticum aestivum* L.	Poaceae
White spruce	*Picea abies* (L.) H. Karst.	Pinaceae
White willow	*Salix alba* L.	Salicaceae
Wormwood	*Artemisia absinthium* L.	Asteraceae
Yajé	*Diplopterys cabrerana* (Cuatrec.) B. Gates	Malpighiaceae
Yerba mate	*Ilex paraguariensis* A. St.-Hil.	Aquifoliaceae

Appendix 1: Common names, binomial and author citation and family for plants and ferns cited in the text. Family designation follow the Angiosperm Phylogeny Group II. Syn. = synonym.

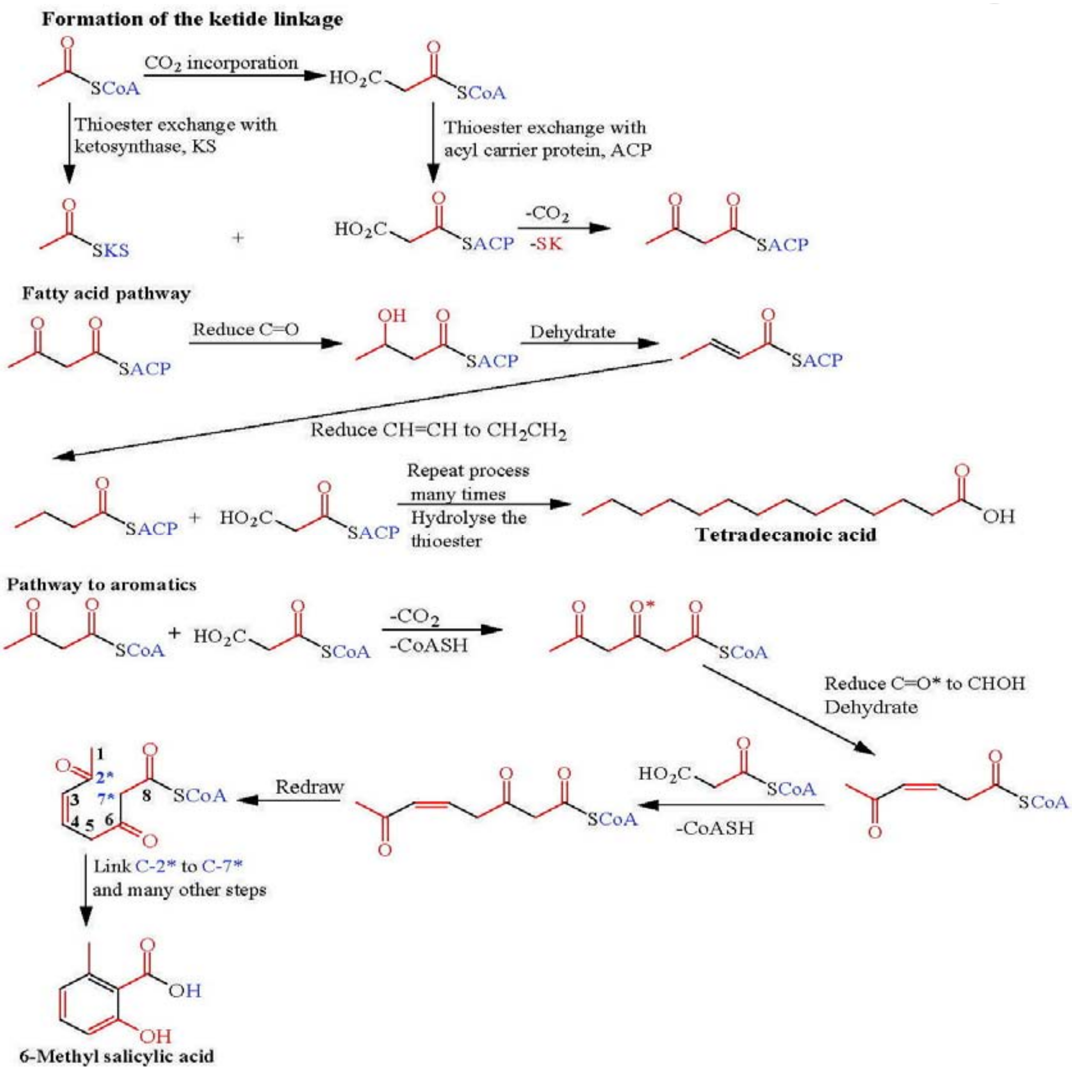

Figure 4. Biosyntheses of tetradecanoic acid and methyl salicylic acid. Individual acetic acid units are colored red throughout this figure. Bonds that link the acetic acid units to one another are black. For 6-methyl salicylic acid, the tetraketide is redrawn prior to the cyclization to make it easier to visualize the reaction.

The polyketide pathway generates a host of natural products. We discuss two important compounds formed by extensions of the pathway to provide a flavor of the subtlety of polyketide biosynthesis. The first is the pathway to arachidonic acid and the prostaglandins, which are important metabolites. The second is aflatoxin, which illustrates the challenge in recognizing the origin of a secondary metabolite because of the twists and turns in its biosynthetic pathway.

-
-
-

Bibliography

Arigoni, D., S. Sagner, C. Latzel, W. Eisenreich, A. Bacher, and M.H. Zenk. (1997). Terpenoid biosynthesis from 1-deoxy-D-xylulose in higher plants by intramolecular skeletal rearrangement. *Proceedings of the National Academy of Sciences, USA* 94, 10600–10605. [A discussion of the nonmevalonoid pathway of terpenoid biosynthesis]

Dewick, P.M.. (2002). *Medicinal natural products. A Biosynthetic Approach*, 2nd Edition, New York, USA: Wiley. [A comprehensive review of plant natural products]

Goodwin, T.W. and E.I. Mercer. (1983). *Introduction to Plant Biochemistry*, 2nd Edition. Oxford, UK: Pergamon Press. [Classical overview of plant chemistry]

Groenewald, E.G.and A.J. van der Westhuizen. (1997). Prostaglandins and related substances in plants. *The Botanical Review* 63, 199-220. [Discussion of the taxonomic distribution of plant prostaglandins and their synthesis and biologically activity]

Hanson, B. (2005). *Understanding Medicinal Plants: Their Chemistry and Therapeutic Action*. Binghampton, USA: Haworth Press. [An outstanding and accessible introduction to organic chemistry relevant to medicinal plants]

Harborne, J.B. (1982). *Introduction to Ecological Biochemistry*, 2nd Edition. New York, USA: Academic Press. [A concise overview of the ecological function of plant natural products.]

He, H-P and H. Corke. (2003). Oil and squalene in *Amaranthus* grain and leaf. *Journal of Agricultural and Food Chemistry* 51, 7913-7920. [Documentation of squalene in a plant]

Levin, E. and V. Cherepanova. (1993). Prostaglandins of Tree Plants. *Acta Hort (ISHS)* 344, 188-193. [Quantification of prostaglandin in several temperate tree species]

Padosch, S.A., D.W. Lachenmeier and L.U. Kröner. (2006). Absinthism: A fictitious 19th century syndrome with present impact. Substance Abuse Treatment, Prevention, and Policy, 1, 14. [Availbale online at: http://www.substanceabusepolicy.com/content/1/1/14] [Review of the history of absinthe]

Biographical Sketches

Dr. Quirke obtained his B.S. and Ph.D. (1976) degrees at the University of Liverpool, U.K. He then worked as a Postdoctoral fellow at the University of Bristol, U.K., where he obtained the first fully characterized structure of a fossil porphyrin. After working as a visiting lecturer at the University of Durham, he joined the faculty of the Department of Chemistry (now Department of Chemistry and Biochemistry) at Florida International University (1982). His current research interests include the study of bile pigments in plants and the development of photogenic reactions for chemical education.

Dr. Bennett is Director of the Center for Ethnobiology and Natural Products and a professor in the Department of Biological Sciences at Florida International University in Miami, Florida. He earned a B.A. in Biology and Geology from Bucknell University, and M.S. in Biology from Florida Atlantic University, and a Ph.D. in Botany from the University of North Carolina at Chapel Hill. He was the 2004-2005 president of the Society for Economic Botany and currently is an associate editor of the journal Economic Botany. He also is a member of the American Botanical Council's Advisory Board and the National Institutes of Health's National Center for Complementary and Alternative Medicine Special Emphasis Panel. His main research focus is Neotropical ethnobotany and ethnopharmacology. Dr. Bennett and his graduate students work in Bolivia, Brazil, Cameroon, Cuba, Costa Rica, Ecuador, Guyana, Japan, Mexico, Panama, Peru, and the U.S. Dr. Bennett's book Ethnobotany of the Shuar of Amazonian Ecuador won the 2006 Klinger Award from the Society for Economic Botany. His research has been published in Ambio, BioScience, Brittonia, Economic Botany, Selbyana, Journal of Tropical Ecology, and Journal of Ethnopharmacology.