*Kirk-Othmer Encyclopedia of Chemical Technology.*
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# DYES, NATURAL

From the earliest of times humans admired the beautiful natural colors of plants and minerals, and sought to enhance human appearance through color. To do so, they painted their bodies with various natural dyes. The ancient Celtic people used the blue dye from the woad plant; the Aztecs in South America used the red dye from the cochineal bug. As time went on, natural dyes were used more and more as cosmetics: hair was dyed, lips were painted, and cheeks were rouged. Some dyes found questionable use in the treatment of illness. Natural dyes were used to make foods and wines more attractive, although many times they were used to disguise an inferior or spoiled product. But the greatest use for natural dyes occurred when the art of weaving developed. A few synthetic dyes were developed before 1856, but without impact. Then, in 1856, Perkin laid the foundation for the synthetic dyestuff industry by his synthesis and manufacture of the dye Mauve. In quick succession, a number of other synthetic dyes appeared on the market, and the natural dyestuff industry was doomed. Natural dyes were replaced by synthetic dyes, although lately there has been a revival of the use of natural dyes for coloring foods, and some textile manufacturers are using natural dyes for dyeing their products. This article discusses those natural dyes formerly manufactured.

## 1. Anthraquinones

The anthraquinone structure occurs in both the plant and animal kingdom. Those natural dyes having this structure surpass all other natural dyes in fastness properties (see Dyes, Anthraquinone).

### 1.1. Alizarin.

There is only one significant plant anthraquinone dye, alizarin [72-48-0] (CI Natural Red 6, 8, 9, 10, 11, and 12; CI 75330). In ancient times, alizarin was the preferred red dye. Cloth dyed with it has been found in Egyptian tombs dating 6000 years ago. The dye is found in the madder plant, a member of the Rubiaceae family. In 1944 about 35 species of this plant were known (1), but the use of more sophisticated analytical methods led to the detection of many more species; by 1984 the number had increased to 50 (2). Of these, *Rubia tinctorum* and *R. peregrina* yield the greatest amount of dye, about 1–2% (3). *R. tinctorum* and other species are perennials growing wild in many parts of Asia, Europe, and tropical zones. In Asia Minor madder was known as lizari or alizari, hence the name alizarin for the dye. The madder plant was not only the source of the red dye but was used also as barter. In Tibet, salt was exchanged for madder and taxes were paid with it (4). Madder was not harvested before a minimum of 18 months and a maximum of 28 months in order to obtain the greatest yield of dye. The dye is concentrated, as a glycoside, mainly in the roots of the plant; the roots were dug, washed, dried, and sold as a finely ground powder. The tops of the plant, containing small amounts of dye, were often used as fodder. Sheep that ate such fodder developed a purple wool (5). Also, in 1736, it was observed that the bones of swine fed on madder were tinted red (6). This observation was used later in studying bone growth (7).

In France and Holland, farmers were well aware that madder roughage had a tendency to impart a reddish hue to milk and a yellowish hue to butter (6).

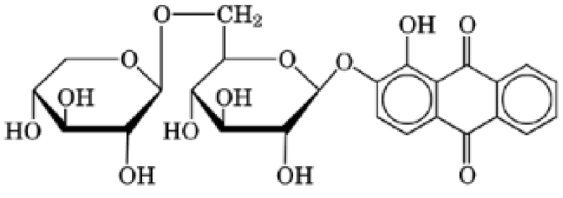
Alizarin was sold in various forms depending on how it had been prepared: Garancine, Garanceuz or spent garancine, Flowers of Madder, and Commercial Alizarin (8). The garacine grade was obtained by treating the madder roots with water acidified with sulfuric acid (9). Garancin is the French name for madder.

Cultivation of madder reached its highest degree in France and Holland during the sixteenth century. In North America, growing conditions were quite suitable, but madder was never cultivated there to any great extent (10).

Alizarin is a mordant dye forming various colored coordination complexes with different metallic salts (11, 12). Based on analytical results, a structural formula has been proposed for the alizarin complex (13).

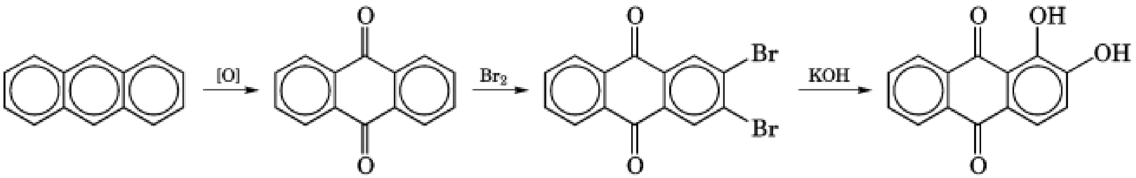
The dyeing of cotton with alizarin originated in India and finally reached Turkey. Originally, alizarin was dyed from a hard water bath containing alum, $KAl(SO_4)_2.12H_2O$, as a mordant. The resulting red color was quite fast and useful for cotton, wool, linen, and silk. However, its shade was rather dull and lacked the brilliancy of kermisic acid-dyed material. In the hands of the Turks, a rather elaborate, drawn-out, and most secretive dyeing process was developed. The result was a beautiful, fiery red, which became known as Turkey Red. Many attempts were made to shorten the process, but the results were far from satisfactory (14).

Scientific investigation of alizarin began in 1816, at which time it was isolated in a pure form as bright orange needles melting at 289–290°C. Alizarin occurs in the plant as a glycoside (15), which became known as ruberythric acid [152-84-1] (16). Enzymic hydrolysis of this produced alizarin and a sugar, primeverose. Much later, ruberythric acid was synthesized and shown to have the structure **(1)** (17):



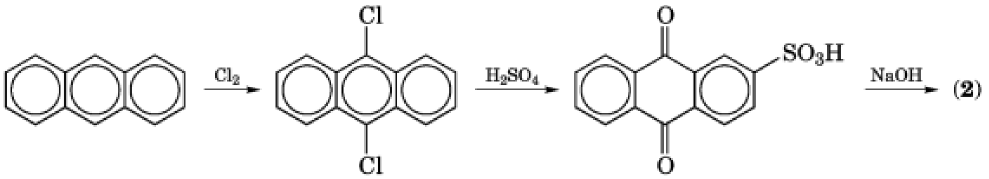
**(1)**

In 1868, alizarin was thought to be a naphthalene derivative. However, upon subjecting alizarin to a zinc distillation, anthracene was obtained. With this information and other data which indicated that alizarin was 1,2-dihydroxyanthraquinone **(2)** (18), anthracene was oxidized to anthraquinone, dibrominated, and the dibromo derivative subjected to a caustic fusion. Alizarin was obtained in an impure form and in low yield. This represented the first synthesis of a natural dye.



**(2)**

This process was not acceptable for several reasons: low yields, poor quality, and the high cost of bromine. Later, at BASF, a process was developed for the manufacture of alizarin by the caustic fusion of anthraquinone-2-sulfonic acid (so-called silver salt) which was made by sulfonating anthraquinone with sulfuric acid. This process was patented in England on the 25th of June, 1869. One day later, W. Perkin applied for a patent for the manufacture of alizarin by a process almost identical to the German process except that the “silver salt” was prepared as follows:



Actually Perkin's process produced a better quality grade of alizarin than that obtained by the German process. To avoid lengthy patent ligitations, both parties agreed to a mutual use of the German patent. Later, improvements were made in the process: use of oleum for sulfonating anthraquinone and the addition of an oxidizing agent to the caustic melt.

For years this was the process used to manufacture alizarin (19) although it was claimed that a more economical process would result if 2-chloroanthraquinone was used instead of silver salt (20). In 1870, the market price for 100% synthetic alizarin was 200 German marks, but by 1912 it had fallen to 5–6 marks, thereby sounding the death of natural alizarin (21). Also, dyers welcomed synthetic alizarin since it was 100% 1,2-dihydroxyanthraquinone; natural alizarin always contained varying amounts of other polyhydroxyanthraquinones.

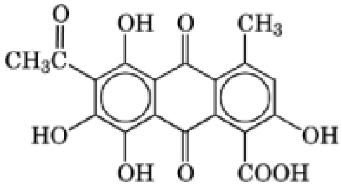
Turkey, for centuries, has been known for the beauty of its handwoven rugs dyed with natural dyes. Nowadays Turkish peasants prefer to dye machine-made rugs with synthetic dyes since these are more readily available and easier to apply. However, there is a growing demand by collectors and connoisseurs connoisseurs for handmade rugs dyed with natural dyes, especially alizarin, and they command premium prices (22). Also, there is a small demand for natural alizarin by artists and home dyers who claim that natural alizarin produces subtle shades not obtainable with synthetic alizarin. Just as synthetic alizarin forced natural alizarin out of the market, synthetic alizarin has been replaced by azoic dyes since they are easier to apply.

### 1.2. Animal Anthraquinone Dyes

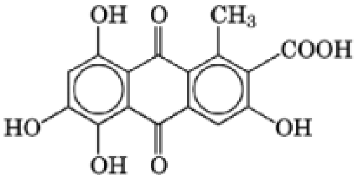
#### *1.2.1. Kermisic Acid*

Many accounts claim that kermisic acid [476-35-7] (CI Natural Red 3; CI 75460) is the oldest dyestuff ever recorded (23). The name *kermes* is derived from an Armenian word meaning little worm for which the later Latin equivalent was *vermiculus*, the basis of the English word vermillion. The dye was obtained from an oriental shield louse, *K. ilicis*, which infest the holm oak *Quercus ilex* and the shrub oak *Q. coccifera*. The dye produces a brilliant scarlet color with an alum mordant. Although expensive, it was cheaper than its rival Tyrian Purple. It was in great demand until the sixteenth century when it was displaced by carminic acid.

Although kermisic acid had been obtained pure as early as 1895 (24), no investigation of the dye was undertaken until 1910 when structural elucidation studies by degradation methods began and it was determined to have the structural formula **(3)**. Synthetic structural proofs were done much later (25, 26) and showed that **(3)** was incorrect. The actual structure of kermisic acid is **(4)**, 1,3,4,6-tetrahydroxy-7-carboxy-8-methylanthraquinone.



**(3)**

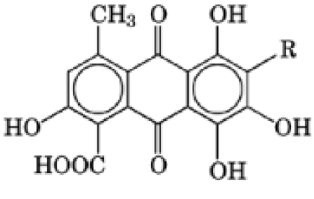


**(4)**

### 1.2.2. Carminic Acid

Carminic acid [1260-17-9] (CI Natural Red 4; CI 75470), is a red dye occurring as a glycoside in the body of the cochineal insect *Dactylopius coccus* of the order Homoptera, family Coccidae. This insect is native to Central and South America. The Aztecs had extracted the dye from the insect centuries before the coming of the Spaniards. For breeding purposes, the insects were collected in the autumn and carefully protected during the winter months. Cochineal was harvested after three months, and then the bugs were killed by immersion in hot water, by placing in hot ovens, or by exposure to the hot sun. The latter method produced the highest quality dye (27). At present, Peru and the Canary Islands are the main source of the dye. Until the advent of synthetic dyes, the principal use for carminic acid was for dyeing tin-mordanted wool or silk. Its aluminum lake, carmine [1390-65-4], finds use in the coloring of foods (see Colorants for foods, drugs, cosmetics, and medical devices).

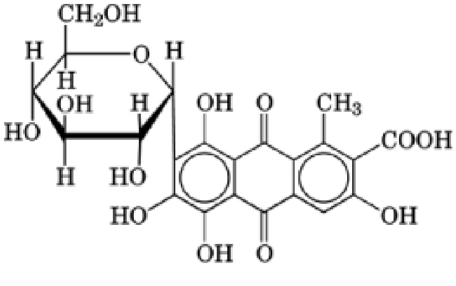
Although carminic acid had been known since 1818 (28), it was not obtained in a pure form until 1858 (29). The structure was finally established as **(5)** (30–33).



**(5)**

At the time the structure of carminic acid was being studied, the composition of the sugar group R was not known. Much later it was shown to be D-glucopy-ranosyl. However, carminic acid did not behave like most glycosides. It resisted all attempts to be hydrolyzed into a sugar and the corresponding aglycone. The problem was resolved when it was demonstrated that carminic acid is a *C*-glycoside (34).

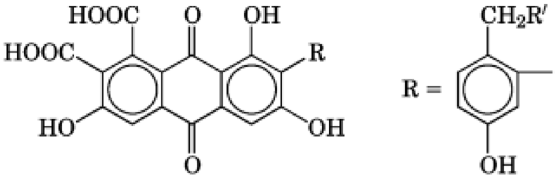
Later studies (35–37) showed that the original assignment of **(5)** was not quite correct. The actual structural formula of carminic acid is **(6)** (38).



**(6)**

### *1.2.3. Laccaic Acid*

This acid has been designated [6219-66-5] (CI Natural Red 25; CI 75450). Lac dye ranks as the most ancient of animal dyes. It is found in lac, the resinous secretion of a very small insect, *Coccus laccae*, found growing in India and Southeast Asia. The word lac is derived from the Hindu word *lakh* meaning one hundred thousand or a great number, having reference to the fact that a great number of these or a great number, having reference to the fact that a great number of these insects had to be gathered in order to produce any quantity of dye. The resinous secretion of the insect is found deposited on branches of trees and is called stick-lac. Water extraction of stick-lac produces the lac dye. The remaining water insoluble material contains several other anthraquinone pigments of minor importance. The lac dye was first investigated in 1887 (39) and named laccaic acid. Structures were proposed for this material (40, 41), but around 1965 it was discovered, chromographically, that lac dye is actually a mixture of acids (42, 43) derived from 2-phenylanthraquinone [6485-97-8]. The acids were designated **A**, **B**, **C**, and **E** (42).



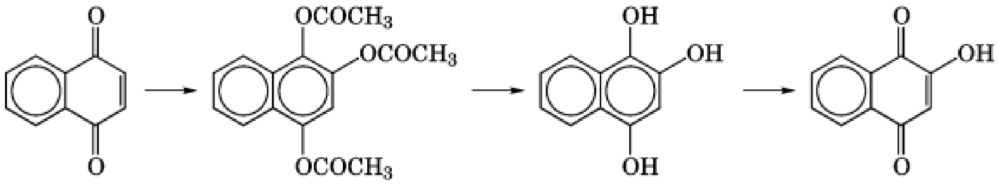
| R′ | |
|---|---|
| $CH_2NHCOOH$ | A |
| $CH_2OH$ | B |
| $CH(NH_2)COOH$ | C |
| $CH_2NH_2$ | E |

An excellent review of this work has been written (38).

## 2. Naphthoquinone Dyes

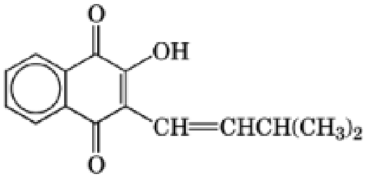
Although naphthoquinones represent the largest group of naturally occurring quinones, only a small number of these achieved importance as dyestuffs.

Lawsone [83-72-7] (CI Natural Orange 6; CI 75420), also known as henna and isojuglone, occurs in the shrub henna (*Lawsone alba*). In England the plant is known as Egyptian privet. The dye was extracted from the leaves of the plant, using sodium bicarbonate, and the extracts used to dye protein fibers an orange shade. Henna is probably the oldest cosmetic known. The ancient Egyptians used it as a hair dye and for staining fingernails. It is said that Mohammed dyed his beard with henna. Lawsone has been identified as 2-hydroxy-1,4-naphthoquinone (44, 45). It has been synthesized by the Thiele acetylation of 1,4-naphthoquinone followed by hydrolysis and oxidation (46):

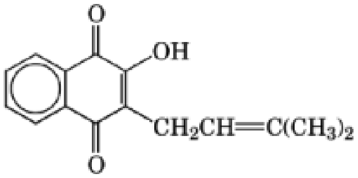


Lapacol [84-79-7] (CI Natural Yellow 16; CI 75490) (lapachic acid, taiguie acid, tecomin) is a yellow pigment occurring in the wood of trees of the genus *Tecoma*, native to the West Indies and tropical South America. The shavings of the wood, treated with lime water, give an extract that dyes cotton yellow.

The pigment was first described in 1866 (47). Based on degradative studies and chemical reactions, it was proposed that lapacol was the alkenylhydroxynaphthoquinone **(7)** (48), but it was later determined that its structure is actually **(8)** (49).



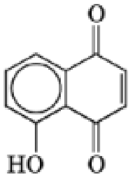
**(7)**



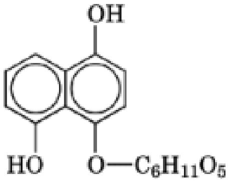
**(8)**

Juglone [481-39-0] (CI Natural Brown 7; CI 75500) was isolated from the husks of walnuts in 1856 (50). Juglone belongs to the Juglandaceae family of which there are a number of species: *Juglans cinerea* (butter nuts), *J. regia* (Persian walnuts), and *J. nigra* (black walnuts). Persian walnuts were known to the ancient Romans who brought them over from Asia Minor to Europe. As early as 1664, the American colonists knew how to extract the brown dye from the nuts of the black walnut and butternut trees, both native to eastern North America (51).

In 1885, from a detailed study of juglone (52) it was proposed that its structure was 5-hydroxy-1,4-naphthoquinone **(9)**. This structure was confirmed by oxidizing 1,5-dihydroxynaphthalene with potassium dichromate in sulfuric acid (53). Juglone occurs in walnuts as a glycoside of its reduced form, 1,4,5-trihydroxynaphthalene (54). Later it was determined that the sugar is in the 4-position **(10)** (55).



**(9)**



**(10)**

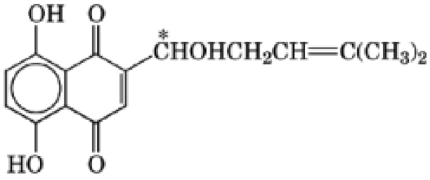
Juglone is most readily synthesized by Bernthsen's method. However, this method is too drastic and results in low yields (56). Somewhat better yields are obtained by using Fremy's salt (potassium nitroso disulfonate) as the oxidant (57). By using thallium trinitrate to oxidize 1,5-dihydroxynaphthalene, yields as high as 70% of juglone have been reported (58).

In the past, juglone had been used to dye wool and cotton a yellowish brown. Although it no longer has any commercial value as a dye, it is a fungicide and as such finds use in the treatment of skin diseases. Its toxic properties have been made use of in catching fish. Juglone has been used to detect very small amounts of nickel salts since it gives a deep violet color with such salts.

Alkannin, shikonin, and shikalkin are grouped together because the first two are enantiomers and the last one is their racemate. Alkannin [577-88-4] (CI Natural Red 20; CI 75530) (*Anchusa tinctoria* or *alkanna tinctoria*) is a member of the Boraginaceae family. It is found in the roots of alkanet, a perennial shrub native to Southern Europe. This reddish dye was used not only for dyeing cloth but also for coloring olive oil, and as a rouge and lip stain. The generic name Anchuss is derived from the Greek word meaning face paint (59).

In the first century, Dioscorides stated that the roots of the anchusa plant were useful in the treatment of wounds (60); this idea has been verified (61).

Alkannin occurs in the roots of the plant as the alkali-sensitive ester of angelic acid (62). It may be extracted from the roots by using boiling light petroleum ether. Treatment of this extract with dilute sodium hydroxide gives a blue solution from which the dye is precipitated by the addition of acid. The crude product is purified by vacuum sublimation (63). Its structure **(11)** is a hydroxylated naphthoquinone with a long, unsaturated side chain (64, 65); it has the (*S*)-configuration.



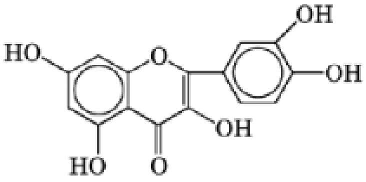
**(11)**

Shikonin [517-89-5] (CI 75535) occurs as an acetyl derivative in the Japanese shikone, *Lithospermum erythrorhizon*, another member of the Boraginaceae family. It is the (*R*)-optical isomer of alkannin (66). Tissue cultures of *L. erythrorhizon* are used in Japan to manufacture shikonin mainly for cosmetic use (67). Both alkannin and shikonin are mordant dyes producing violet to gray colors on fabrics. In Japan, shikonin was used to dye fabrics a color known as Tokyo Violet. Shikalkin [54952-43-1] the racemate (**11**), has been synthesized (68).

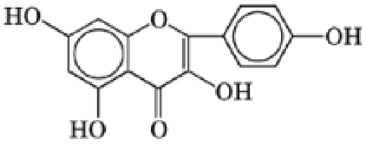
### 2.1. Flavones

These compounds are the most widely distributed natural coloring matter formerly used as dyestuffs. The term flavone was first suggested in 1895 (69), and is indicative of their yellow color (*flavus*, Latin for yellow). They have lost their commercial value as dyes since the advent of synthetic dyes in 1856.

Flavone-type dyes occur in all the higher plants: in the leaves, roots, bark, fruits, pollen, and flower petals. None have been found in fungi, mosses, or lichens. The most widespread flavone dyes are quercetin [117-39-5] **(12)** and kaempferol [520-18-3] **(13)**:



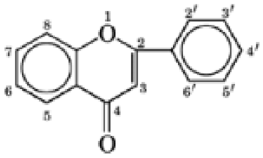
**(12)**



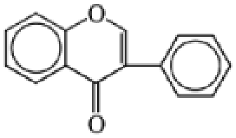
**(13)**

In general, the dyes occur as glycosides, the most common sugar being glucose. Some flavones contain more than one sugar. Their role as dyes in the plant is not definitely known: a common suggestion is that they protect the plant from harmful uv radiation.

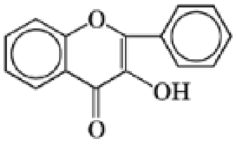
The basic unit of the flavone-type dyes is 2-phenylbenzopyrone **(14)** which unsubstituted is flavone [525-82-6]; isoflavone [574-12-9] is **(15)** and flavonol [577-85-5] is **(16)**.



**(14)**

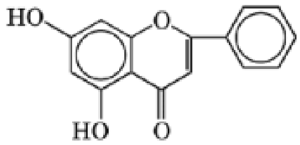


**(15)**

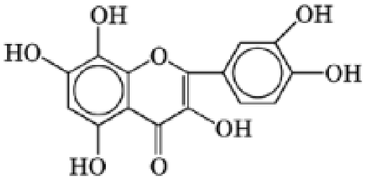


**(16)**

Flavone dyes having these structures are hydroxylated and methoxylated derivatives. The degree of hydroxylation varies from two in chrysin [480-40-0] **(17)** to six in gossypetin [489-35-0] **(18)**. Those dyes containing not more than three hydroxyls are generally termed flavones whereas those containing up to and including six are flavonols.



**(17)**



**(18)**

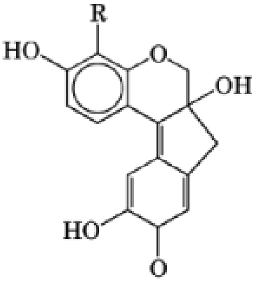
The flavone, isoflavone, and flavonol-type dyes owe their importance to the presence of an *o*-hydroxy carbonyl structure within the molecule. Positions 4 and 5 can chelate with different metallic salts to give colored, insoluble complexes. In other words, these dyes require a mordant in order to fix them onto the fiber. Perkin was able to predict the structure of unknown flavones by comparing the color of their complexes with the color of known complexes (70). For example, ferric chloride gives a green color with 5-hydroxyflavones and a brown one with 3-hydroxyflavones (71).

Chrysin **(17)** was the first flavone to be isolated in a pure form, and its structure was elucidated by identification of its alkaline degradation products (72–74). The structure was confirmed by synthesis (75, 76). The same procedures were used to establish the structure of other flavones and in so doing the foundation of flavone chemistry was laid (77).

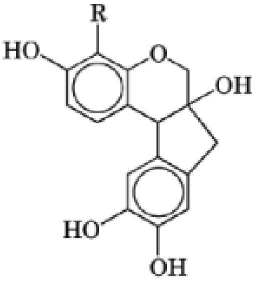
Of all the flavone dyes luteolin [491-70-3] (5,7,3′,4′-tetrahydroxyflavone) is the oldest known European dye. It is found in weld (*Reseda luteola*) also known as dyer's rocket, dyer's weed, and wild mignonettle. Luteolin was well known to the ancient Romans, who used this very pure yellow pigment to dye the garments and robes of the Vestal Virgins (78). Until the middle of the nineteenth century, luteolin top-dyed with indigotin produced good greens known as Lincoln green and Saxon green (79). The naturally occurring flavone-type dyes used commercially until 1856 are described fully elsewhere (80).

Logwood [8005-32-2] (CI Natural Black 1; CI 75290) is a modified benzopyrone, and was the last of the natural dyes to survive after the appearance of synthetic dyes because of the desirable bluish-black hue it produced on chromemordanted fibers. However, for economic reasons and because it requires a mordant, it too is no longer used commercially.

Logwood was discovered originally in Mexico in the Province of Campeche by Spanish settlers who referred to it as *palo de Campeche* (wood of Campeche). The French knew it as *bois de Campeche* and the Germans called it *blauholz* because of its use to give blue dyeings. Sometimes it was referred to as blood wood. Based on this, Linnaeus applied the generic name *Haematoxylon* to the tree from which logwood dyes are obtained. The dye is best known as logwood presumably because it was obtained from logs of wood. These types of dyes were obtained from the wood either by the French or American process. In the American process, the logs are reduced to chips and the dye is extracted with hot water under pressure. The French process did not use pressure. Concentration of the extracts produced dyewood crystals. During the concentration process, the haematein [475-25-2] **(19)** is produced by oxidation of its leuco form haematoxylin [517-28-2] **(20)**.



**(19)** R = OH
**(22)** R = H



**(20)** R = OH
**(21)** R = H

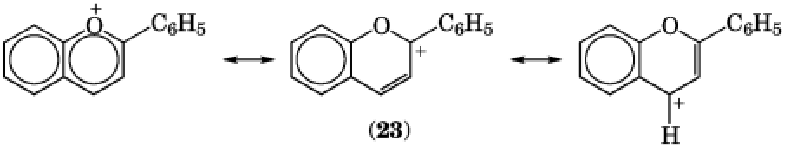
Although logwood had been known for several hundred years, it did not achieve technical importance until it was discovered that it combined with metallic salts to give various colored lakes, of which the chrome lake was the most important (81). After an enormous amount of research, the present formulas for the dye components were proposed (82) and later substantiated (83).

Brazilwood [8005-32-1] (CI Natural Red 24; CI 75280) has long disappeared from the market because of the very fugitive character of its dye. The chemistry of the dye parallels that of logwood in that it has a leuco form, brazilin [474-07-7] **(21)** and its oxidation product brazilein [600-76-0] the dye **(22)**. It differs from logwood in that it has one less phenolic group. The dye occurs in trees belonging to various species of *Caesalpina*, and is extracted from the wood of these trees by a process similar to that used for logwood. The name brazil has its origin in the Portuguese word *braza* referring to anything having a bright red color. More about the history of brazilwood may be found in the original literature (84).

### 2.2. Anthocyanins

Like the flavones, the anthocyanins are found throughout nature. This class of polyphenolic compounds is responsible for the pink, red, violet, and blue colors found in plants. The term anthocyan is derived from the Greek words *antho* for flower and *kyanos* for blue. It was proposed first to denote the blue color of the cornflower (85). Later, as knowledge about plant pigments increased, the term was extended to include all such pigments and the ending “in” was added. Like many other natural phenolic substances, anthocyanins occur in plants as glycosides; the sugar-free anthocyanins are known as anthocyanidins.

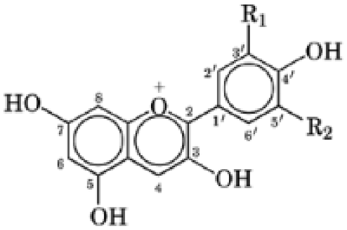
All anthocyanidins have the 2-phenylbenzopyrylium or flavylium cation structure (86, 87) **(23)**, a resonance hybrid of oxonium forms and carbenium forms [14051-53-7]:



**(23)**

In all these structures, the anions are $Cl^-$.

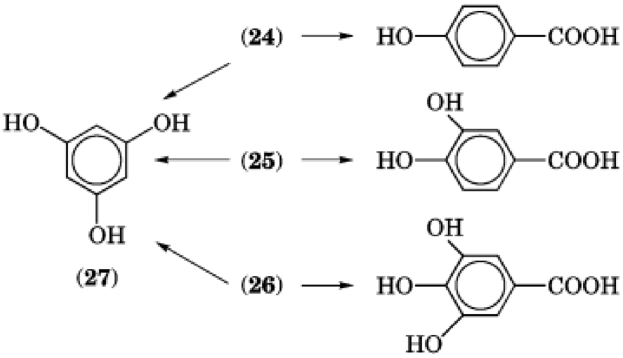
There are three fundamental groups of anthocyanidins to which all the other anthocyanidins could be referred (88–90). In the following structure $R_1 = R_2 = H$ designates pelargonidin **(24)**; $R_1 = OH$, $R_2 = H$ is cyanidin **(25)**; and $R_1 = R_2 = OH$ is delphinidin **(26)**.



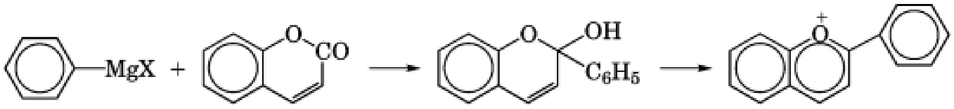
The anthocyanins are pH sensitive. Their color, in part, is determined by the pH of the sap. Cyanin, for example, is red at pH 3, violet at 8, and blue at 11. However, there are other factors that affect the colors of the anthocyanins; metallic salts, notably iron and aluminum, react with those anthocyanins containing vicinal hydroxy groups and produce highly colored complex compounds. Other factors are the colloidal condition of the cell sap and copigmentation (91).

All the anthocyanins, when boiled for a short time with hydrochloric acid, yield one or more sugars and anthocyanidin. The most frequently occurring sugars are glucose, rhamnose, galactose, and gentiobiose. Of these, glucose is the most prevalent. In most cases the sugars are found in the 3- and occasionally in the 5-position. In some cases, the hydroxyl group of the anthocyanin or that of the sugar may be esterified with an organic acid such as the *p*-hydroxy derivative of benzoic, cinnamic, coumaric, or malonic acid (92).

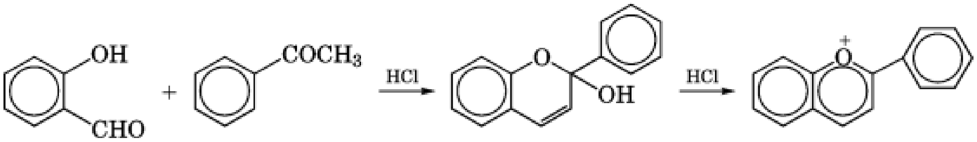
Alkaline degradation was used to determine the structure of pelargonidin [134-04-3], cyanidin [528-58-5], and delphenidin [528-53-0] by treating each of them with concentrated potassium hydroxide at 140–150°C (89). Each of them produced phloroglucinol **(27)** and the corresponding phenolic benzoic acid:



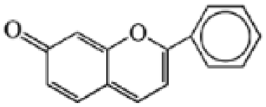
Anthocyanidins were first synthesized by reaction of an aryl Grignard reagent with a coumarin (93).



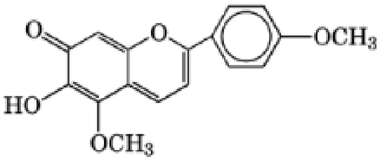
A more convenient method for synthesizing anthocyanidins involves the condensation of an *o*-hydroxybenzaldehyde with an acetophenone (94).



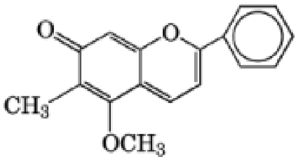
Because of their pH sensitivity, anthocyanins have found little use as industrial dyes. However, a few having the quinoidal form of anthocyanidin **(28)** were formerly used as dyes. Two of these were carajurin [491-93-0] **(29)** and dracorhodin [643-56-1] **(30)**:



**(28)**



**(29)**



**(30)**

## 3. Indigoid Dyes

### 3.1. Tyrian Purple

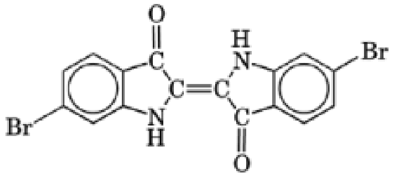
The ancient kingdom of Tyre owed its fame and fortune to the purple dye produced from the lowly mollusks found on its shores. From early Egyptian and pre-Roman times, about 1600 BC, it was known that these shellfish produced a secretion which, on exposure to light and air, produced a beautiful and fast purple dye. The dye became known as Tyrian Purple [19201-58-7] (CI 75800) reflecting its place of origin. These mollusks belong to the Muricidae family and the genera *Murex* and *Purpura* which include *M. brandaris* and *M. trunculus*, the principal sources of the dye.

There are a number of myths relating to the discovery of Tyrian Purple. One such goes as follows: a Tyrian god was walking along the shore accompanied by his dog and a nymph. Suddenly the dog bit into a shellfish, whereupon his mouth became stained a beautiful purple. Seeing this, the nymph begged the god to have a dress made for her dyed with this new dye. He granted her wish and won her everlasting favor.

Tyrian Purple was the most expensive and rare dye of the ancient world principally because only a small amount of dye could be obtained from each mollusk, roughly 0.12 mg (95). It was always considered a color of distinction and restricted to regal and ecclesiastical uses; in the Eastern Roman Empire, the heir to the throne at Byzantium bore the proud name *Porphyro-Genitur*, born to the purple. The Hebrews used purple in many decorations of the Tabernacle (23).

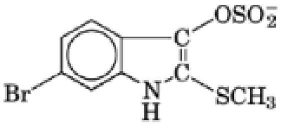
Pliny described the manufacture of Tyrian Purple, which was dependent on the species of mollusk used. In the case of the large mollusk, *M. brandaris*, a single drop of granular secretion was extracted from a gland adjacent to the respiratory cavity. In the case of the smaller mollusk, *M. trunculus*, the entire mollusk was crushed and used as such. Irrespective of the method used, the next step consisted in salting the material for about three days, followed by boiling the entire mass for 10 days (96). Sometimes other dyes, such as kermisic acid, were added in order to alter the shade of the dye. Around 1453, the Turks overran the Eastern Roman Empire and destroyed the Tyrian dye plants. From then on, extracting purple dye from shellfish practically ceased.

Toward the latter part of the seventeenth century it was observed that the natives of Ireland were dyeing linen and silk with a secretion from shellfish found along the Somerset and Welsh coast. Cloth dyed with this secretion, when exposed to sunlight, underwent a series of color changes ultimately resulting in a bright crimson color on the fiber. These observations awakened general interest in this dye extracted from mollusks (97). In the period that followed, a number of investigators made valuable contributions about the dye (98). For example, from about 12,000 mollusks ~1.4 g of dye were isolated, and it was determined that the dye was 6,6′-bromoindigotin [19201-53-7] **(31)** (99). This structure was confirmed by synthesis (100).

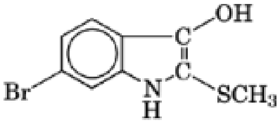


**(31)**

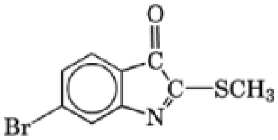
The next important investigation of Tyrian Purple was the determination of the precursor of the dye. Several investigators critically examined the composition of the hypobranchial gland and established that it varied from one species of mollusk to another. In general, the glands were extracted with either alcohol or ether or a combination of both, the extracts were purified by gel and thin-layer chromatography, and the structure of the precursors determined by elemental analysis and spectroscopic methods. Some species of mollusk contained more than one precursor, for example, *Dicathais orbita* contains one (101), whereas *M. trunculus* has four (102). The principal precursor isolated from the glands was sodium 6-bromo-2-methylthioindoxyl sulfate **(32)** (tyrindoxyl sulfate). Also isolated was a quinhydrone mixture consisting of 6-bromo-2-methylthioindoxyl **(33)** and 6-bromo-2-methylthioindoleninone **(34)** (tyriverdin). Both tyrindoxyl sulfate [74626-31-6] and tyriverdin produce purple colors. A summary of this work has been reported (103).



**(32)**



**(33)**



**(34)**

### 3.2. Indigotin

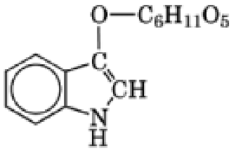
The blue dye of the ancient world was derived from indigo and woad. Which plant is the oldest is a matter of conjecture. That indigo was known at least four thousand years ago is evident from ancient Sanskrit writings. Cloth dyed with indigotin [482-89-3] (CI Natural Blue) (CI 75780) has been found in Egyptian tombs and in the graves of the Incas in South America. The history of indigo is better documented than that of woad because indigo was indigenous to such wide areas as Asia, Java, Japan, and Central America (104). Woad, on the other hand, was found mainly in Europe. During their conquests in the New World, the Spaniards found Indians who painted their bodies with indigotin, dyed fabrics with it, and used it to paint ceramic vessels.

Indigo belongs to the legume family. Over three hundred species belong to this family, many yielding indigotin in varying quantities. The two most important species are *Indigo tinctoria* and *I. suffruticosa*, found in India and the Americas, respectively. Unaware of the true nature of indigotin, the Romans called it *Indicum* meaning a product from India. Ancient dyers who used indigotin called it *nil*, which ultimately led to the Arabic word *al-nil* meaning blue, and to our word aniline.

Because of the long overland route used to bring indigotin from India to Europe, and because of the small amount of indigotin that was present in the leaves, about 2–4%, indigotin ranked among the most expensive of the ancient dyes (105).

Indigotin was a very profitable item because of cheap labor, and many nations set up indigo plantations in various parts of the world: Spain in Guatemala, France in its Caribbean colonies, and England in the West Indies and India (106). In India, England, represented by its East India Company, had problems arising mainly from its poor economical treatment of the ryots who toiled in the indigo fields. This led to the so-called Blue Mutiny of 1859–1862 (107). As early as 1649, half-hearted attempts were made to grow indigo in America. It was not until 1739 that an indigo plantation was established in South Carolina as a result of the untiring efforts of a Miss Eliza Lucas who later became Mrs. E. Pinckney (108). So successful were her efforts that by 1773 over 500 t of indigo had been exported to England. Ultimately, because of the American Revolution, indigo lost its importance.

The leaves of the indigo plant do not contain the dye as such, but in the form of its precursor, a glycoside known as indican (109). Indican [487-60-5] is the dextrose derivative **(35)** of indoxyl [480-93-3] (110). Indoxyl occurs also in the urine of humans as the potassium salt of indoxyl sulfonic acid (111).



**(35)**

The process used to manufacture indigotin from the plant remained unchanged throughout hundreds of years. An old seventeenth century print shows the equipment used to prepare indigotin (112). A series of tanks are arranged step-wise one above the other. Into the uppermost one, the fermentation tank, water and the freshly cut plants are placed. Here indican is hydrolyzed into indoxyl and glucose by an enzyme known as indimulsin (113). During the fermentation, a vigorous evolution of carbon dioxide occurs along with a gradual color change in the broth. After nine to fourteen hours, the yellowish liquor is drained from the top tank into the next lower one via a spigot. In this tank the indoxyl is air-oxidized to indigotin by agitating the liquor with paddles. As it gradually forms, indigotin settles to the bottom of the tank. The supernatant liquor is siphoned off and the indigotin removed to another tank where it is heated to prevent further fermentation. Then it is filtered, placed into trays and air-dried to a thick paste. The paste is cut into bricks and sold as such. Indigotin was the first of the so-called vat dyes because the entire operation was carried out in tanks or vats.

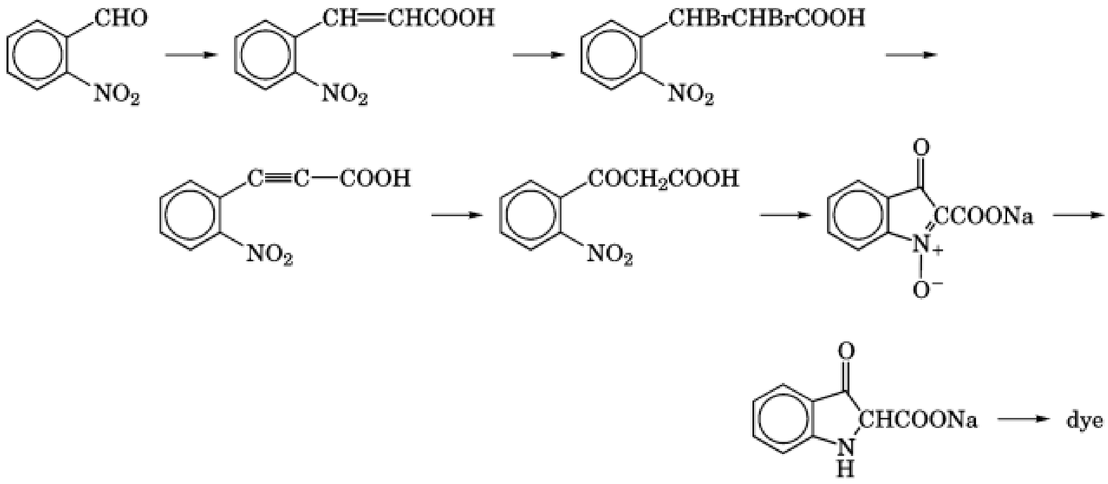
Indigotin did not appear in Europe until the twelfth century. Venice, because of its strategic land and sea position, was the first European city to receive and use indigotin. However, the further spread of foreign indigotin throughout Europe was strongly opposed by the Europeans because it would compete with indigotin from woad, an ancient and widely cultivated plant. When Caesar invaded England in 55 BC, he encountered a race of people who stained their bodies blue with indigotin from woad (114).

Cultivation and use of woad was a primary industry throughout Europe. Indigotin from abroad would have had disasterous consequences on the economy and lives of many people. Farmers, merchants, and dyers banded together in order to convince the authorities that foreign indigotin was the devil's dye and corrosive to cloth dyed with it. To strengthen their argument, deception was employed whereby corrosive salts were added to the dye bath. Ultimately laws were passed that blocked the use of foreign indigotin in Europe. For the next three or four hundred years, only indigotin from woad was used in Europe.

Woad, *Isatis tinctoris*, belongs to a genus that comprises some thirty species. The plant is widely distributed in many parts of Europe, especially France, England, Germany, and Holland. Woad was probably the first blue dye plant cultivated in America. Undoubtedly it was brought over from England by the early colonists (115). The name woad is derived from the Anglo-Saxon *wad* or *waad.* Because of its weedy nature, its original German name was *weedt* or *weeda*, which may be the origin of our word weed (116).

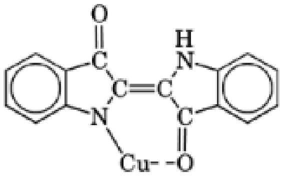
The method for preparing indigotin from woad differed radically from that used for making indigotin from indigo, possibly because of differences in the dye precursor (117). The fresh woad leaves were ground into a pulp, which was then made into piles for draining. The piles were formed into balls and these dried on racks for one to four weeks. The dried balls were ground to a powder and the powder then spread into layers about one-half to one meter deep. The layers were wet with water, constantly stirred, and left to ferment for about nine weeks. After this time, the dark, clay-like mass was shaped into balls and sold in this form (117). Woad indigotin was about 10% weaker in dye strength than imported indigotin. Ultimately, dyers preferred indigotin from indigo, so that by the seventeenth century woad indigotin had practically disappeared from the marketplace.

Many investigators attempted to unravel the structure of indigotin, including von Baeyer who developed a number of syntheses for the dye. Some of these he believed had potential for the manufacture of the dye. One of these syntheses is shown (118):



This process was sold to BASF in 1897 for $100,000, but never achieved commercial success.

Baeyer assigned a cis-form to indigotin, but x-ray crystallographic studies indicated that the dye molecule has a center of symmetry that is only possible if the molecule has a trans-configuration (119). Many derivatives of indigotin have been prepared that would not have been possible if indigotin had a cis-structure, eg, **(36)** (120).

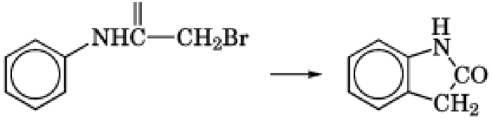


**(36)**

Although there is complete agreement that indigotin has a trans-configuration, many questions remain regarding some of its physical properties (121).

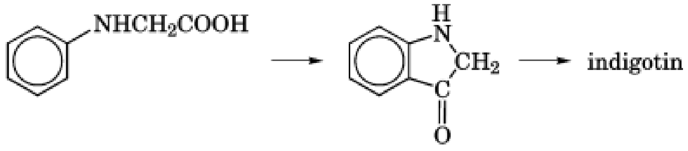
Baeyer's investigation of indigotin spanned a period of almost 20 years. In 1905, he received the Nobel Prize in recognition of his accomplishments.

In 1890, it was observed that treatment of $\omega$-bromoacetanilide with alkali produced oxindole [59-48-3] (122) **(37)**:



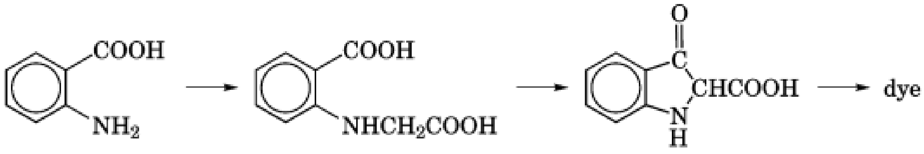
**(37)**

Based on this observation, K. Heumann treated *N*-phenylglycine [103-01-5] with alkali and obtained indoxyl **(38)** (keto form), which on aerial oxidation converted to indigotin:



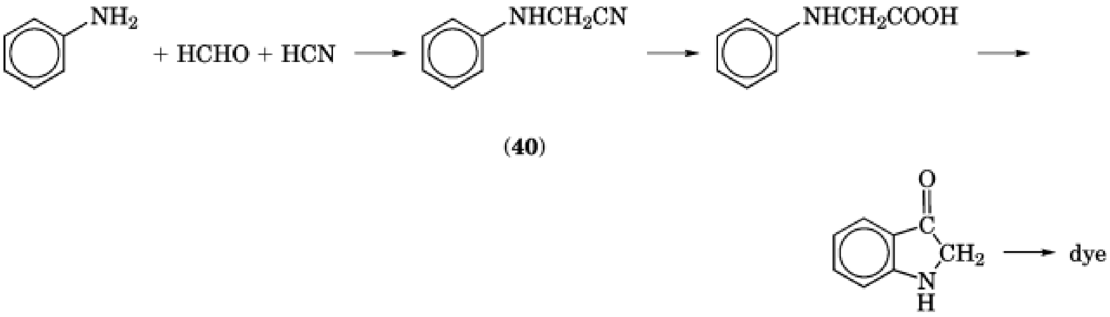
**(38)**

This was the first practical approach to the manufacture of the dye (123). The patent to this process was shared jointly by BASF and Hoechst (124). The yields by this process were so bad that Heumann developed another process involving the use of anthranilic acid [118-92-3] **(39)** (made from naphthalene).



**(39)**

This was the process used by BASF and Hoechst for about 30 years. Later, a variation of the original Heumann process was made: aniline, formaldehyde, and hydrogen cyanide react to form phenylglycinonitrile **(40)** which is hydrolyzed to phenylglycine. This is the most widely used process for manufacturing indigotin.



**(40)**

The greatest improvement in the manufacture of indigotin came when sodamide was used with alkali in the conversion of phenylglycine to indoxyl (125). Not only was the fusion temperature lowered from about 300°C to 200°C, but also the reaction was made practically anhydrous by the sodamide reacting with any water present. The result was an almost quantitative yield of dye.

After the second World War, German firms manufacturing indigotin faced serious competition from English and American dyestuff companies. To counteract this, the Germans developed continuous operations for manufacturing the dye. However, because of the complexity of the equipment and the operations (126), the batch process is still the preferred manufacturing method.

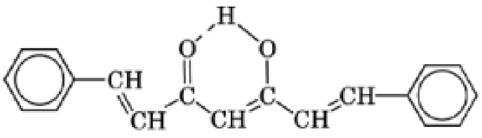
Although there is still demand for indigotin for dyeing blue jeans, it has lost a good part of the market to other blue dyes with better dyeing properties. At present, practically all the indigotin consumed in the United States comes from abroad.

Indigotin is available as a 100% pure powder and as a 20% solution. As of February, 1992, the powder form sold for about $20/kg in 80-kg lots. Most of indigotin is sold in solution form.

## 4. Natural Food Colors

The use of natural dyes as food colorants has a long and not always an admirable history. Pliny, the Roman scholar, records the use of various vegetable extracts to give young red wines the appearance of mature claret (127). As late as the latter part of the nineteenth century, the juices of the red beet and pokeberry were added to red wine. This stemmed from the fact that the price paid for red wine depended on the richness of its color. In 1892, the use of pokeberry extract was prohibited since it contains an emetic and a purgatory substance (128). Other foods besides wine were artificially colored. In 1935, the government of Paris forbade the coloring of butter since this was often done to conceal an inferior product. For the most part, colorants used for foods were fairly innocuous, but in the early part of the nineteenth century sweets were often colored with metallic salts such as lead chromate or copper arsenite. Obviously some form of legislation was called for to protect people from the improper and harmful use of food additives. Largely through the efforts of Dr. Harvey W. Wiley, who was chief chemist of the agriculture's bureau of chemistry, the Foods and Drug Act of 1906 was initiated (see Colorants for foods, drugs, cosmetics, and medical devices). In the 1970s, decertification of the important food colors FD&C Reds 2 and 4 caused much concern among manufacturers of food dyes. With the possibility that other synthetic dyes would be banned, attention was turned to the use of natural dyes as food colorants. Many such dyes had been in use for hundreds of years until they were replaced by synthetic dyes.

The yellow dye curcumin, [458-37-7] (CI Natural Yellow 3; CI 75300) **(41)**, also known as tumeric, occurs in the roots of the plant *Curcuma tinctoria* found growing wild in Asia. The dye was well known to the ancient Romans and Greeks who used it to dye wool, cotton, and silk. The dye is an oil-soluble bright yellow material, and is the only natural yellow dye that requires no mordant. It finds use as a colorant for baked goods such as cakes.



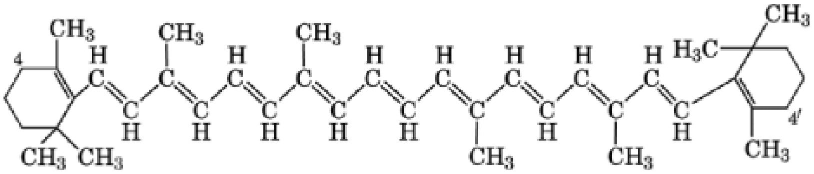
**(41)**

Carmine [1390-65-4] is the trade name for the aluminum lake of the red anthraquinone dye carminic acid obtained from the cochineal bug. The dye is obtained from the powdery form of cochineal by extraction with hot water, the extracts treated with aluminum salts, and the dye precipitated from the solution by the addition of ethanol. This water-soluble bright red dye is used for coloring shrimp, pork sausages, pharmaceuticals, and cosmetics. It is the only animal-derived dye approved as a colorant for foods and other products.

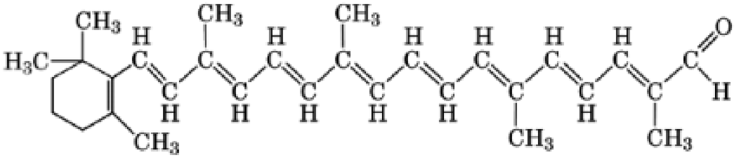
### 4.1. Carotenoids

The carotenoids are a group of widely distributed, highly colored, fat-insoluble, naturally occurring organic compounds. They owe their color to the four repeating isopyrene units found in the molecule and may, therefore, be classified as tetraterpenoids. The carotenoids may be divided into two principal groups, the carotenes, which are strictly hydrocarbons, and the xanthophylls, which contain oxygen. Carotenoids are found in almost all fruits and vegetables, egg yolk, dairy products, and sea foods. The chemistry of the carotenoids has been described in a number of reviews (129).

Although the carotenoids can be obtained from natural sources, it is far more economical to manufacture them for commercial use (130). Three have been manufactured for many years: $\beta$-carotene [7235-40-7] (**42**), canthaxanthin [514-78-3] (**43**), and $\beta$-apo-8′-carotenal [1107-26-2] (**44**) (131). Their structures are shown in Figure 1.



**(42)**



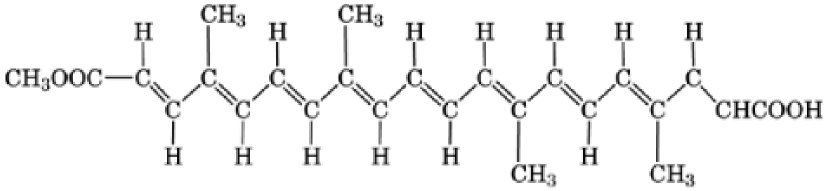
**(44)**

**Fig. 1.** Carotenoid pigments: β-carotene (**42**), β-apo-8′-carotenal (**44**), and canthaxanthin (**43**) $_{=\text{structure}}$ (**42**) with ketone groups at the 4 and 4′ positions.

In general, the low solubility of the carotenoids creates a problem when they are applied as food dyes. β-Carotene, for example, has poor solubility in fats. To overcome this, a microcrystalline powder form has been prepared. This is then mixed into an edible fat. In this form it finds use for coloring margarine, butter, cake mixtures, and other fat-containing foods. β-Carotene is available also as an emulsion, in a water-dispersed form, and as a liquid suspension. Canthaxanthin is commercially available as a 10% water-dispersable beadlet or spray-dried powder. Because of its exceptionally good tomato color-enhancing properties, it finds use in tomato-based products such as pizza and spaghetti sauce. It is useful in water-based foods such as peach ice cream and pink grapefruit beverages. β-Apo-8′-carotenal has high tinctorial strength; because of this, it is marketed in several different strengths, usually as a dispersion in vegetable oils. Its main use is for coloring process cheese and French dressing.

Carotenoids have two general characteristics of importance to the food industry: they are not pH sensitive in the normal 2–7 range found in foods, and they are not affected by vitamin C, making them especially important for beverages. They are more expensive than synthetic food dyes and have a limited color range. In their natural environment they are quite stable, but they become more labile when heated or when they are in solution. Under those conditions, there is a tendency for the trans-double bonds to isomerize to the cis-structure with a subsequent loss of color intensity. The results of controlled tolerance and toxicity tests, using pure carotenoids, indicate that they are perfectly safe as food colors (132).

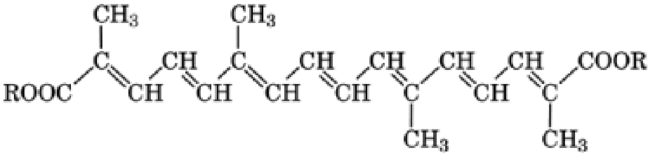
Bixin [6983-79-5] (CI Natural Orange 4; CI75120) **(45)** is found in the seeds of the plant *Bixa orellana* native to India.



**(45)**

Later it was found growing in South America where the Indians used the red dye from the seeds as a body paint. An extract of the seeds appears on the market as annatto. This extract is used in coloring butter, margarine, and cheese such as Leicester cheese. In Mexican and South American cuisine, it finds special use as a flavor and coloring matter. The seeds are sold under the name achiote in many Latin grocery stores and markets. Annato is available as an aqueous solution, as an oleaginous dispersion, and a spray-dried powder.

Crocetin [27876-94-4] (CI Natural Yellow 6; CI 75100) occurs in saffron as crocin [42553-65-1] **(46)**, the digentiobiose ester of crocetin **(47)**.



**(46)**, **(47)**

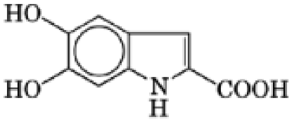
R = H for crocetin (**47**) and R = gentiobiose for crocin (**46**)

Saffron is found in the pistils of the plant *Crocus sativus*. Saffron is often confused with safflower, sometimes known as bastard saffron. The name of the plant, *Crocus sativus*, comes from the Arabic word *za faran*, meaning yellow. The Romans and the Greeks used saffron not only as a dye but also as a spice. In the early days of Greece, yellow was the official color, and Grecian women were especially fond of clothes dyed with saffron. Because of its scarcity, saffron ranked among the most expensive dyes of the ancient world.

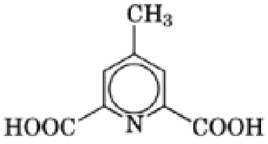
### 4.2. Betalaines

In 1968, the term betalaines was used to describe collectively two groups of plant pigments: the red betacyanins and the yellow betaxanthins. The red and yellow dyes found in beets, *Beta vulgaris*, fall into this category. An interesting history has been written about these dyes (133).

In 1918, a crude sample of the dye was prepared, as the glycoside betanin, and named betacyane (134). Alkaline hydrolysis of betanin yielded glucose, but the sensitive aglucone could not be isolated. Betanin contains nitrogen and, in some respects, is like an anthocyanidin. This led some investigators to believe that betanin was a nitrogenous anthocyanidin (135). In the meantime, a pure crystalline sample of betanin had been prepared electrophoretically (136). The pure betanin was cleaved enzymatically and yielded the aglucone betanidin (137). Alkaline degradation of betanidin produced 5,6-dihydroxyindol-2-carboxyl acid [4790-08-3] **(48)** and 4-methylpyridine-2,6-dicarboxylic acid [75475-96-6] **(49)** and ammonia (138):

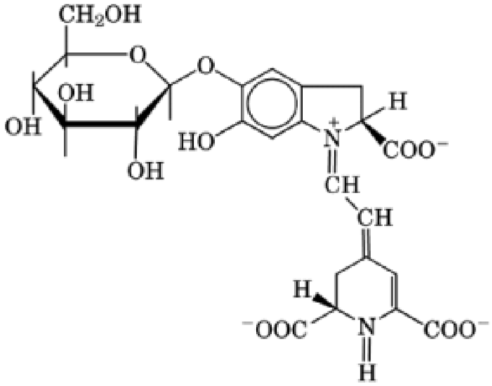


**(48)**

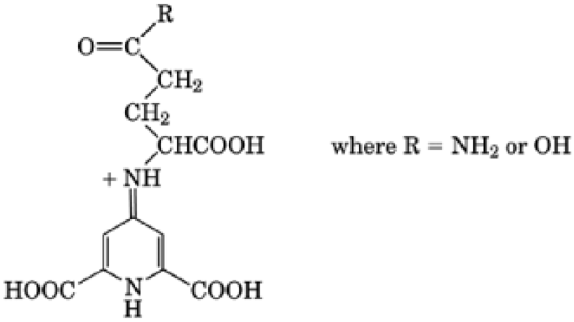


**(49)**

The study of these fragments, coupled with the results of additional research (139), established the structure of betanin [7659-95-2] **(50)**. Betanidin [37279-84-8] was synthesized in 1975 (140). A small amount of two yellow pigments is present also in beets **(51)**. These have no value as food dyes.



**(50)**



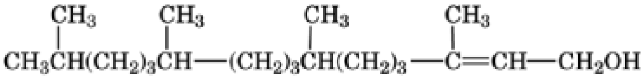
**(51)**

The color of betalaines is barely affected by the pH range normally found in foods. However, the dyes are heat sensitive, which places some limitations on their use as food dyes.

Beet juice contains about 80% of fermentable carbohydrates and nitrogenous compounds. To remove these compounds, a yeast fermentation utilizing *Candida utillis* has been suggested (141). By so doing, a more concentrated form of the dye becomes available. The red dye from beets is sold as beet juice concentrate, as dehydrated beet root, and as a dried powder.

### 4.3. Chlorophyll

The determination of the structure of chlorophyll involved the efforts of many famous chemists, notably R. Willstätter (Nobel Prize 1915) who, during the period 1906–1914, laid the foundation for the future investigation of chlorophyll (142). He not only prepared relatively pure chlorophyll for the first time, but also isolated two different modifications of the molecule. These he designated as a- and b-chlorophyll. H. Fischer (Nobel Prize 1930) suggested the structural formula for chlorophyll based on his work with hemin. In 1960, R. B. Woodward (Nobel Prize 1965) and his co-workers synthesized chlorophyll and hemin (143). Chemically pure chlorophyll is difficult to prepare, since it occurs mixed with other colored substances such as carotenoids. Commercially it is solvent extracted from the dried leaves of various plants such as broccoli or spinach (144). Chlorophyll is water-insoluble. It has none of the characteristics of a dye in that it has no affinity for the usual fibers such as cotton or wool. Chlorophyll is properly classified as a pigment [8049-84-1] (CI Natural Green 3;CI 75810). As such, it finds use for coloring soaps, waxes, inks, fats, or oils. Chlorophyll is an ester composed of an acidic part, chlorophyllin, esterified by an aliphatic alcohol known as phytol **(52)**:



$$CH_3\overset{\overset{CH_3}{|}}{C}H(CH_2)_3\overset{\overset{CH_3}{|}}{C}H-(CH_2)_3\overset{\overset{CH_3}{|}}{C}H(CH_2)_3-\overset{\overset{CH_3}{|}}{C}{=}CH-CH_2OH$$

**(52)**

Hydrolysis of chlorophyll using sodium hydroxide produces the moderately water-soluble sodium salts of chlorophyllin, phytol and methanol (145). The magnesium in chlorophyllin may be replaced by copper. The sodium copper chlorophyllin salt is heat stable, and is ideal for coloring foods where heat is involved, such as in canning (146).

## 5. Health, Safety, and Environmental Factors of Natural Dyes

Natural dyes comprise those colors derived from plant or animal matter without chemical processing. They have been known and used for thousands of years without any reports showing that they are harmful. Modern tests have verified the safety of natural dyes as food colorants; many of these dyes are on the FDA's list of approved food dyes. The FDA no longer looks upon long usage of natural dyes as a criterion of safety. Any new natural dye must conform to the rules and tests established by the FDA. There are no new reports indicating that natural dyes cause health problems, although some fruit juices, colored with natural dyes, have caused diarrhea among children who drank excessive amounts of such juices.

Natural dyes processed for the market do not undergo any chemical operations. Those operations involved are purely physical, such as grinding, spray or vacuum drying, and water or solvent extractions. None of these operations create any great environmental problems.

The use of natural dyes as food colorants evolved over a period spanning thousands of years. During that period, by trial and error, some dyes were found to be safe while others were not. By comparison, the development of synthetic dyes as food colorants has taken place over a comparatively short time. During that period, some synthetic dyes considered safe by existing health standards were used as food colors. Later, with increased knowledge, these were found to create health problems and were removed from the marketplace. The manufacture of synthetic dyes for use on foods creates more of a health and environmental problem than natural dyes, but offers greater variety and stability of color (see Dyes, environmental chemistry).

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