THE IMPORTANCE OF ANTHOCYANINS IN PLANTS

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Abstract
This article discusses the biological role of anthocyanins in plant life, their chemical structure, synthesis, and specific properties in color formation. Anthocyanins are found in various tissues of plants, provide their color diversity, and play an important role in adapting to environmental stress factors. Their effect on color depends on the pH level of the environment, metal ions, and other physicochemical factors. The article also provides information on the use of anthocyanins in the food industry and medicine. The results of the study contribute to a deeper understanding of the practical importance of anthocyanins in plant ecology and human activity.

Keywords: Anthocyanins, Flavonoids, Plant pigments, Color change, pH Level, Metal ions, Environmental stress, Biosynthesis, Food dyes, Cyanide.

Introduction

Pigments (lat. pigmentum — dye) are coloring compounds that are part of the tissues of organisms. The color of the pigment is associated with the chromophore group in their molecule that selectively absorbs visible light (380-750 nm) of the solar spectrum. The pigment is part of cytochromes, catalase and other enzymes, membrane structures, forms complexes with proteins and lipids. In the cell, the pigment is located in special structures (chloroplasts, chromoplasts, etc.), sometimes in the cell sap. Most animals have special pigment cells. The pigment is of great importance in photobiological processes (photosynthesis, vision, photoregulation); participates in respiration (hemoglobin, cytochromes, chromogens), protects the body from ultraviolet radiation (in plants - carotenoids and flavonoids, in animals - melanins), determines the color of animals and plants. Pigments are used in the food and pharmaceutical industries. Highly dispersed powdery coloring substances that are insoluble in water, organic solvents, film-forming substances and other dyeing media (unlike dyes). Pigments improve the properties of films that protect materials from corrosion. Organic pigments are synthetic coloring substances with a different chemical structure. Mono- and disazopigment products are important. They range in color from greenish yellow to dark red[12].

The Main Part

Anthocyanin is an antioxidant that gives blueberries their color, has powerful properties for fighting inflammation and protecting cells. In addition, the product, which has a natural sweet taste, contains almost no calories compared to some other sweeteners. But there are many other reasons to add blueberries to everything you eat. Anthocyanins are glycosides of oxygenated heterocyclic compounds (anthocyanidins). Anthocyanins give plants their various colors. The color of a plant depends not only on the anthocyanin, but also on the amount of water in the plant cells and on the metal with which the anthocyanin is combined. For example, anthocyanin is red when combined with iron, blue and pink with molybdenum, and white with nickel or copper. Anthocyanin is broken down into sugars and anthocyanidins when boiled with acids (or under the influence of enzymes). The sugar part of anthocyanins can often be glucose, rhamnose, or galactose[13].

Biological and chemical significance of anthocyanins

Anthocyanins (from the Greek “anthos” - flower and “cyanus” - blue) are glucosides widely distributed in the plant world. They are broken down by the action of certain enzymes or when boiled with alkalis to form carbohydrates and anthocyanins. Anthocyanidins are salts of oxyflavones. The color of flowers and fruits is due to the presence of anthocyanins - pelargonidin (1), cyanidin (II), delphenidin (III) and apigenidin (IV). The core underlying anthocyanidins differs from the flavone core in two important features: There is no ketone group in the heterocyclic ring. It is in the form of a benzopyrylium salt, that is, it has the same electronic structure and properties as heterocyclic aromatic compounds. An increase in the number of oxygen atoms in the anthocyanidin molecule leads to the formation of a large amount of pigment

Anthocyanidins change their color depending on the pH of the environment. Most anthocyanidins are purple in a neutral environment, red in an acidic environment (in the case of benzopyroxonium salts), and blue under the influence of alkalis (anthocyanidin - in the base). For example, let's see how the color of cyanidin changes depending on the environment; So, one pigment appears in different colors depending on the environment. Therefore, in nature, flowers are of different colors due to the presence of the same pigment in different pH environments. A clear correlation has been established between the color of flowers and the structure of anthocyanins. When studying the systematic structure of candle-colored flowers, it was revealed that pelargonidin is present in their composition. Red berries are known to contain delphinidin, while purple berries are known to contain blue. Berries, raspberries, plums, and apples produce red fruits with anthocyanins. This indicates that the fruits are not ripe. Many black fruits, such as black grapes, are usually very dark red in color due to the presence of anthocyanins. The main reason for this emphasis is that red wine is made from black grapes and its content of anthocyanins is relatively low. Anthocyanins are present not only in the fruit of plants, but also in the leaves or stems, and these parts of the plants are colored.[13] Anthocyanins are usually produced in large quantities in young shoots and leaves. The red color of autumn leaves may also be the result of the synthesis of anthocyanins. The breakdown of chlorophyll in autumn makes the anthocyanin color more pronounced. The color given by anthocyanins, especially in flowers and fruits where the quinoid form of the pigment is dominant, may be due to the formation of chelate complexes with metals and copigmentation. Anthocyanins with dihydroxy substituents form chelate complexes with metal ions, causing the pigment to shift. This makes the blue color more pronounced. An example of this is the widespread hydrangea plant. In this plant, the anthocyanin delphinin-3-glycoside is present in the petals of the flower, but in many flowers this anthocyanin forms complexes with ammonium and molybdenum ions. If the soil is rich in these metal ions, the plant will produce blue flowers on the stem, even if it was originally pink. If these salts are low in quantity, the blue flowers will turn pink. Most breeding programs are aimed at selecting flowers with better, i.e., intense or sparse, color. In biochemical terms, the meaning of the work is to change the quality and quantity of anthocyanins. The pigments of red and blue flowers belong to the group of oxonium salts of 2-phenylchromium, which do not contain a carbonyl group. Of these, pelargonidin, cyanidin, and delphinidin are most often found in the form of salts[13]. Pelargonidin is the simplest representative of anthocyanins. It is a pigment of common geranium flowers, and is also a pigment of ripe raspberries and strawberries. Cyanidine gives color to blackcurrants, raspberries, strawberries, cherries, apples, and the bark. The color of cyanidine changes depending on the acidity of the medium. In an acidic environment, it is red, and in an alkaline environment, it is blue. Nature is very economical here, in fact, the different colors of the blue cornflower and the red tulip are due to the same pigment. The fact is that cornflower juice is slightly alkaline, in such an environment the cyanide molecule loses a hydrogen atom and turns blue. On the contrary, the juice of the tulip is acidic. In an environment rich in hydrogen ions, the cyanide molecule attaches to one of them and turns red.

The participation of anthocyanins in the process of photosynthesis.

Anthocyanins are not directly involved in photosynthesis; instead, they protect the photosynthetic machinery, primarily chlorophyll, from excess light. They act as a photoprotective "sunscreen" by absorbing high-energy light wavelengths (e.g., blue-green) that would otherwise overwhelm the chloroplasts, a process known as photoprotection.

Interaction of anthocyanins with photosynthesis:

Photoprotection: When light intensity is too high, anthocyanins absorb and dissipate excess energy, preventing damage to the photosystems within the chloroplasts.

Photoinhibition: This protection is especially important during the early stages of plant growth, when the leaves are still developing and have an immature photosynthetic apparatus.

Light filtering: Anthocyanins act as optical filters, reducing the amount of high-energy light reaching the chloroplasts, which could cause damage.

No direct role: unlike chlorophyll, which absorbs light to convert energy, anthocyanins are secondary pigments located in the plant vacuole and do not transfer the absorbed energy to the photosynthetic apparatus.

"Anthocyanin-dependent anoxygenic photosynthesis": In some special cases, such as in some flower petals, there is evidence that anthocyanins may participate in photosynthesis by absorbing light energy, although this is not the typical role of anthocyanins in leaves[6]. Anthocyanins are known to appear in several plant species at different stages of their life cycle, such as in the immature stage (Hughes et al., 2007, Solovchenko and Chivkunova, 2011), in winter (Hughes et al., 2005, Hughes, 2011) and in senescent autumn leaves (H20). In several plant species that show anthocyanin pigmentation in young leaves, the anthocyanin disappears with leaf maturity. Various explanations have been given for this, one of which is to protect the immature photosynthetic apparatus from damage by solar radiation. Anthocyanin pigments are present in the solar spectrum acts as a light absorber, protecting the main cells from high irradiance by absorbing high-energy blue-green wavelengths (Hatier and Gould, 2009, Chalker-Scott, 1999). Anthocyanin pigments do not transfer the absorbed light energy to the photosynthetic apparatus (Hogewoning et al., 2012). In immature leaves, chloroplasts are not fully developed and the chlorophyll content per unit leaf is low, so there is an imbalance between the light-capturing capacity and the CO 2 assimilation capacity, which makes immature leaves vulnerable to photoinhibition (Krause et al., 1995). As a result, young leaves growing under high irradiance are more susceptible to photosynthetic saturation and photoinhibition at much lower light intensities than mature leaves (Hoflacher and Bauer, 1982). Therefore, leaf Early in development, light deprivation is generally beneficial [7].

Many studies have shown that anthocyanin synthesis and accumulation are dependent on light intensity (Paiva et al., 2003, Nguyen and Cin, 2009). Light regulation of anthocyanin synthesis may indicate that the physiological role of anthocyanins depends on light absorption or its utilization in the leaf. Anthocyanin content in Corylus avellana leaves was found to be positively correlated with photosynthetic electron transport rate (ETR), and red leaves showed a higher ETR dependence at higher values of photosynthetically active radiation (PAR) than green leaves (Solovchenko and Chivkunova, 2011), indicating the influence of light on the photosynthetic process. In addition, anthocyanins perform several functions in plants, including protection against low temperatures, drought, soil salinity, antioxidant functions, and other stress factors.

Jatropha curcas is a multipurpose small tree, and jatropha seeds contain a sticky oil that can be used as a diesel substitute or extender to prevent soil erosion and prevent land reclamation. This latter use is important and therefore may prove to be a promising species for biodiesel production (Openshaw, 2000, Diaz-Lopez et al., 2012). J. Curcas trees are easy to establish and grow relatively quickly and have a good canopy with moderate to abundant foliage (Sunil et al., 2013). Thus, they are good at fixing atmospheric carbon and storing it in the wood and contributing to the accumulation of carbon in the soil. J. Curcas growing in Lucknow, North India, show the onset of new leaves with the onset of spring in early March (Ranjan et al., 2012) and leaf emergence continues until the onset of monsoon (July). These new leaves are dark red on both surfaces and turn green when mature. Young leaves of J. curcas, along with mature leaves, are exposed to the harsh summers of Lucknow, where light intensity reaches 2000 μmol m -2 s -1 and temperatures exceed 40 °C and the leaf-to-air vapor pressure deficit

(VPD) is about 6.0 KPa (Shirke, 40 and Shirke). As mentioned above, several studies have been conducted on many plants with anthocyanins in their young leaves and various roles have been identified for the presence of anthocyanins. J. curcas leaves begin and mature during the peak summer months when light and temperature are maximum. Therefore, light attenuation should be particularly beneficial for J. curcas leaves.

The role of anthocyanins in enhancing plant stress tolerance

Global climate change has led to an increase in extreme weather events, and plants have been exposed to various abiotic stresses. Plants rooted in the soil cannot escape abiotic stress by moving. Therefore, plants have developed complex mechanisms to cope with abiotic stress, which negatively affects photosynthesis, respiration, cell water potential, and ultimately normal growth and development. Anthocyanins, a type of flavonoid, are natural water-soluble pigments of various colors in plants and can protect plants from various environmental stresses. Anthocyanins have antioxidant functions and play an indispensable role in scavenging reactive oxygen species (ROS). In addition, anthocyanins act as “sunscreens” and chelate metals with metalloids to alleviate metal stress. However, the biosynthesis and stability of anthocyanins are affected by various external factors. Here, we review the regulatory mechanisms of anthocyanin synthesis, the effects of environmental factors on anthocyanin production, and the role of anthocyanins in plant responses to environmental stresses such as drought, salt stress, high light intensity, ultraviolet light, heavy metals, and low temperature. Given the important role of anthocyanins in stress tolerance, increasing anthocyanin content by manipulating regulatory genes may be beneficial for improving plant stress tolerance, which is a potential solution for tolerance to extreme environments today and in the future[4].

Soil salinity is a major problem that is increasing due to climate change and anthropogenic impacts, and poses a serious threat to global food security by impairing plant growth, development, and productivity. Salinity stress induces osmotic, ionic, and oxidative stresses, disrupting physiological and biochemical processes in plants. Anthocyanins, a class of flavonoids, have emerged as key players in mitigating salt stress through their antioxidant properties, scavenging ROS, and regulating stress response pathways. During salt stress, ROS act as damaging agents and signaling molecules by regulating anthocyanin-related genes to mitigate oxidative stress and maintain cellular homeostasis. Anthocyanins mitigate salt stress by regulating osmotic balance, ionic homeostasis, and antioxidant defense. Their biosynthesis is regulated by a network of structural and regulatory genes, including the transcription factors MYB, bHLH, and WD40, under the influence of epigenetic modifications and hormonal signaling pathways such as ABA, JA, and SA[2.3].

Advances in genetic engineering, including CRISPR/Cas9-mediated gene editing, have enabled the development of anthocyanin-rich transgenic plants with improved salt tolerance. For example, transgenic plants overexpressing anthocyanin biosynthesis genes such as DFR and ANS have shown salt tolerance in crops such as tomato and rice. However, challenges remain, such as variability in anthocyanin accumulation and stability under environmental stresses. This review highlights the translational potential of anthocyanins in crop improvement and emphasizes the need for integrated multi-omics approaches and field trials to validate their efficacy. By elucidating the molecular mechanisms of salt stress and anthocyanin-mediated stress mitigation, this work provides a basis for developing resistant crops to address the growing challenges associated with soil salinity.

The well-known fact of the activation of anthocyanin biosynthesis in plants under stressful conditions still lacks a deep physiological and biochemical basis. It is likely that anthocyanins do not carry any functional load, but are synthesized as the final products of the saturated flavonoid pathway, which takes the vacuolar branch for the final deposition of phenolic compounds unnecessary for the plant. On the other hand, the induction of anthocyanins under the influence of certain environmental factors, as well as the predictability of the appearance of anthocyanins at specific stages of leaf development from year to year, their precise expression in specific ecological niches, may help plant organisms adapt to specific stress conditions[1].

Many popular books incorrectly state that the color of autumn leaves (including red) is simply the result of the destruction of green chlorophyll, which masks the yellow, orange, and red pigments (xanthophyll, carotenoid, and anthocyanin, respectively). And while this is true for carotenoids and xanthophylls, anthocyanins are not present in leaves until the chlorophyll level in the leaves has decreased. It is precisely when plants begin to synthesize anthocyanins, perhaps for photoprotection during nitrogen fixation. Anthocyanins are widespread pigments in the plant kingdom. They belong to the flavonoids formed in the branched phenylpropanoid pathway of biosynthesis, which evolved as a result of the adaptation of plants to a terrestrial lifestyle Ferrer L, (2008). The biological role of flavonoids is to attract animals as pollinators and seed dispersers, to facilitate the interaction of plants with each other and with microorganisms, and to participate in stress responses.

The processes of anthocyanin pigment in cotton plants

Inheritance of the color of the corolla of cotton plants. The work of many researchers is also devoted to the study of the inheritance of this character. Fyson P.F. (1908) studied the white corolla of Indian cotton plants of Djori and Boni. Inheritance of plant color. Anthocyanin color is not evenly distributed in cotton plants. Anthocyanin (red) pigment is found in the hypocotyl, seed coat, true leaves, corollas and cotyledons. For diploid species, 6 alleles of the R gene, which encodes the anthocyanin pigment, have been identified: R, RL, RC, RS, rO and rG. In this case, the R allele controls the anthocyanin color in the inflorescence, RL controls the red color of the leaves, RC controls the red color of the sepals, RS controls the anthocyanin spot at the base of the corolla, rO controls the absence of anthocyanin spot, rG controls the development of a weak anthocyanin spot at the base of the corolla (Hutchinson, 1932, 1937). In the tetraploid G. hirsutum L., the R1 gene, which controls the anthocyanin color in the inflorescence, controls the anthocyanin pigment in the plant part and is located in linkage group III (Harland, 1935; 1939; Kohel, 1972) [10].

The expression of anthocyanin in the vegetative and generative organs of New World cotton is determined by Stephens (1948, 1969, 1974) due to the influence and interaction of two genetic loci, called R1 and R2. The R1 gene is known among G. hirsutum L. cotton, and the R2 gene among G. barbadense L. cotton. The R h gene, which controls the expression of the “red leaf” and “red stem” phenotypes in cotton, is common to both species and has been shown to be inherited in an incompletely dominant manner and controlled by a single gene. Kohel (1972) included the R1 gene, which controls plant color, in linkage group III, and the R2 gene, which controls the anthocyanin stain on the base of the corolla, in linkage group I. Anthocyanins are found in special vesicles - anthocyanoplasts, chloroplasts, as well as in the plasma of some types of onions and in the cell sap of orange fruits in the form of crystals[14].

The well-known fact of activation of anthocyanin biosynthesis in plants under stressful conditions does not yet have a deep physiological and biochemical basis.

It is possible that anthocyanins do not carry any functional load, but are synthesized as the final product of the saturated flavonoid pathway, which takes the vacuolar branch for the final deposition of phenolic compounds unnecessary for the plant. On the other hand, the induction of anthocyanins under the influence of certain environmental factors, as well as the predictability of the appearance of anthocyanins from year to year at specific stages of leaf development, their specific expression in specific ecological niches, may contribute to the adaptation of plant organisms to certain stress conditions.

CONCLUSION

To date, all stages of anthocyanin biosynthesis and the enzymes that carry them out are known and have been thoroughly studied using biochemistry and molecular genetics. Structural and regulatory genes for anthocyanin biosynthesis have been isolated from many plant species. Understanding the specific biosynthesis of anthocyanin pigments in a particular plant species allows for genetic manipulation of its color, creating plants with unusual pigmentation that can be passed down from generation to generation.

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