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The biology of rudraksha

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Rudraksha, used throughout India and Southeast Asia in religious jewellery, is the stony endocarp of a tree distributed from northern Australia to southern Nepal. This article summarizes its biology, particularly recent research on the remarkable fruit colour. The iridescent blue colour is caused by a remarkable structure, an 'iridosome'. It is secreted by the epidermal cell, and is located above the plasmalemma and beneath the adaxial wall. Cellulosic layers within the iridosome constructively interfere with blue wavelengths, causing an intense colour production at 439 nm. This colour persists in senescing fruits and may enhance their dispersal. The transparency of the cuticle at longer wavelengths allows photosynthesis to occur in the fleshy green exocarp tissue, enhancing the carbon balance of the tree. More research will certainly reveal the evolution of this remarkable phenomenon, as well as the origins of the rudraksha's cultural use.

THE fruits of *Elaeocarpus*, a genus of some 360 species in the Elaeocarpaceae[1], all contain hard and highly ornamented endocarps (Figure 1). The round endocarps of *E. angustifolius* Blume [synonyms include *E. ganitrus* Roxb. and *E. sphaericus* (Gaertn.) K. Schum. (ref. 2)], are especially attractive and have been used for religious purposes in India for some two millennia, known as *rudraksha*. Beads of various plants, including rudraksha, are strung together as rosaries, or *malas*. The use of such jewellery among all religions may have originated in India[3]. *E. angustifolius* is a relatively fast-growing tree, most common in secondary forest. It grows wild in tropical forests in Queensland, New Guinea, Malaysia, and southern Nepal. The traditional economic value of rudraksha makes it difficult to ascertain its natural distribution. It may have been introduced by Hindu missionaries and traders in some of these areas. Even today it is imported to India from Indonesia, where some villagers in Java and Bali have developed special techniques for reducing the size of the 'bead'[4]. Rudraksha is particularly associated with Saivism; the Sanskrit word *rudraksa* (रुद्राक्षा) contains the roots *rudra-*, the vedic name for Siva, and *aksha-*, most probably meaning eye (Wilhelm Rau, pers. comm.). The *Devi Bhagavata* [Skandha 11][5] described these beads as coming from the tears of Siva, after he sat in meditation for a thousand years. The sculpturing of the bead surface appears as 'faces', associated with the locules of the ovary, normally five in number (Figure 1). Abnormalities with fewer or more locules have special significances, as described in the *Siva Purana* [Skandha 25][5]. Here I describe the biology of these culturally important fruits.

Production and dispersal

The fruits of rudraksha are produced some five months after flowering (Figure 2), the timing of which varies

Figure 1. Rudraksha fruits, approximately 22 mm in diameter, showing the relationship of the hard endocarp to the fleshy exocarp, the 'faces' corresponding to locules in the ovary, with a single seed revealed in cross-section.

Figure 2. Flowers of rudraksha, *Elaeocarpus angustifolius*, photographed from planted trees in Miami, October 1990. Flowers are approximately 1 cm in length; note the small immature fruits.

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in different locations. The fruits are blue in colour, characteristic of most of the taxa in the genus, but most brilliant in *E. angustifolius*. Although fruits consumed and dispersed by birds are generally red, some 5–7% are also blue[6]. The endocarp of rudraksha, typically some 14 mm in diameter, is surrounded by fleshy green mesocarp that extends the fruit diameter to approximately 22 mm (Figure 1). In parts of its distribution rudraksha fruits are known to be consumed by large birds, particularly the cassowaries and fruit pigeons of Queensland and New Guinea[7,8]. Perhaps they are also consumed by the moonbacked imperial pigeon (*Ducula badia*) in moist South Asian forests. The exocarp supplies a nutritious reward to consumers, particularly rich in carbohydrates (21.0% dry mass, or 0.58 g per fruit) and proteins (4.3% dry mass, or 0.12 g per fruit), but lacking in lipids (E. D. Stiles, unpublished research). The oily texture of the flesh, which is responsible for the generic name (*elaeo* – is the Greek root for olive or olive oil), is more likely due to the production of mucilaginous compounds. Birds consume the fruits whole, strip the fleshy exocarp in their crops, and pass the endocarp through the digestive tract. Seedlings emerge some months later, after the tough endocarp breaks open.

Structural fruit colour

Corner[9] had remarked that the brilliant blue colour of the fruit is 'caused, not by a blue pigment, but by the structure of the cuticle which reflects blue light; thin pieces of skin are green in transmitted light'[9]. Blue fruit colour is normally caused by anthocyanins, modified by their association with metals or other flavonoid pigments[10]. However, no such anthocyanins were extractable in acidic methanol in rudraksha fruits, suggesting that the basis for colour production may well be structural[11]. Three physical methods produce colour in animals: thin film interference, Tyndall scattering, and diffraction[12]. As for iridescent coloration in leaves[13], the basis of the blue iridescence in rudraksha fruits also appears to be thin film interference. Analysis of diffuse reflectance (Figure 3) indicated a strong peak at 439 nm; Tyndall scattering would not produce such a peak, and diffraction would produce colour more dependent upon the angle of incidence.

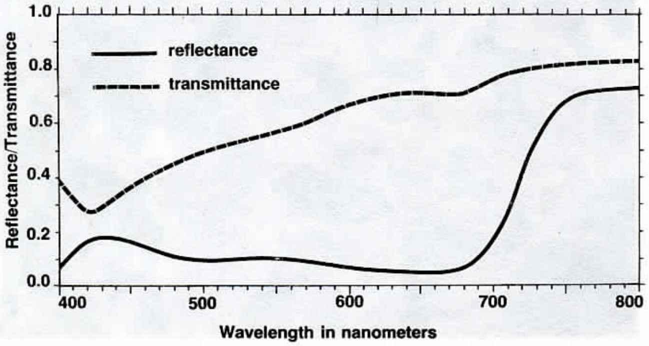

Figure 3. Reflection of light, and transmission through the cuticle of rudraksha fruits[11]. Note that the reduction in transmission at approximately 439 nm is accompanied by relative high transmission at longer wavelengths.

Filter location

The iridosome can be located as a structure whose thickness is predicted by the classical laws of interference. Layers with indices of refraction different than the surrounding medium destructively interfere with light at a thickness 1/4 the wavelength of light in the medium (depending upon the refractive index). The same layer will constructively interfere with a thickness of 1/2 the wavelength, causing the apparent reflectance of intense colour (thickness = $\lambda/4\mu\cos\theta$, where θ is the refracted angle of light in the filter, μ is the refractive index of the film (where μ is greater than the surrounding medium), and λ is the peak wavelength for constructive interference).

The blue coloration of rudraksha fruits is not reduced by immersion in water; if anything the intensity is enhanced. In *Selaginella willdenowii* and *S. uncinata* blue leaf iridescence was removed by contact with water, suggesting a location at the surface of the upper epidermis[14,15]. In other iridescent-leaved plants, colour was not affected by contact with water, indicating a location beneath the surface[16,17]. For rudraksha, a measurement

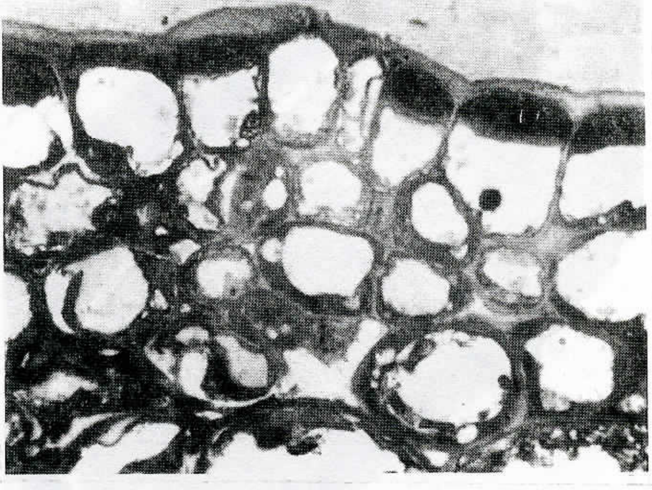

Figure 4. Light micrograph of the transverse section of the cuticle, epidermal cells, and cortex of a rudraksha fruit. The iridosomes avidly take up toluidine blue and appear almost black in this micrograph. Bar indicates 20 μm.

of peak diffuse reflectance of 439 nm (Figure 3)[11], assuming a refractive index of 1.35–1.45 for the layer[18,19], allows a prediction of a filter thickness of 76–81 nm, beneath the cuticle of the fruit.

Ultrastructure

Locating such a filter requires the resolution of transmission electron microscopy (TEM). Through TEM I found a remarkable structure, located above the plasmalemma of the epidermal cell, but beneath the cuticle and cell well (Figures 4 and 5)[11]. I have called this structure an 'iridosome', based on analogous structures discovered in animals[12]. The iridosome consists of a roughly parallel network of electron-translucent strands forming a network[11] (Figure 5). The entire structure is visible through light microscopy because of its strong affinity for toluidine blue stain (Figure 4). That, and other histochemical stains, indicate that the principal constituent of the structure is cellulose. The strands are approximately 78 nm thick, separated by lacunae of 39 nm. A peridermal section of the same structure (Figure 6) reveals that the network may have a three-dimensional organization, analogous to the space lattice structures in the morpho butterfly[20] and the peacock[21]. Scanning electron microscopy was of insufficient resolution to reveal this organization (Figure 7), although the structural integrity of the iridosome was revealed.

These results suggest a means of structural coloration fundamentally different than that found in the iridescent blue leaves of tropical rain forest understory plants[15–17]. In most, the basis for the filter is a series of layers in the cell wall, as in *Selaginella*. For some of these taxa, the shift in the angle of deposition of successive microfibrils creates a helicoidal appearance. The periodicity of this structure is a basis for constructive interference, as in the Malesian fern *Diplazium crenatoserratum* (Figure 8). Other plants produce iridescence through the modification of chloroplasts, mostly in the epidermis (Figure 9). In the fruits of rudraksha, the

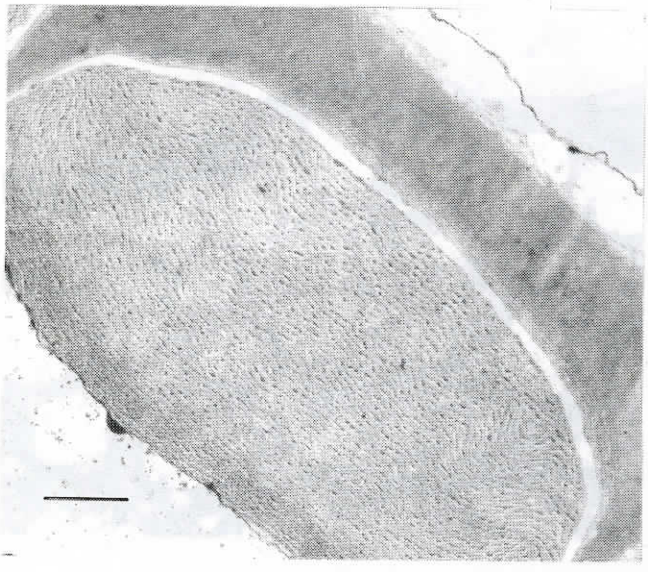

Figure 5. TEM photograph of the transverse section through a portion of the epidermal layer of a rudraksha fruit. Note the thin layers that make up the iridosome. Bar indicates 1 μm.

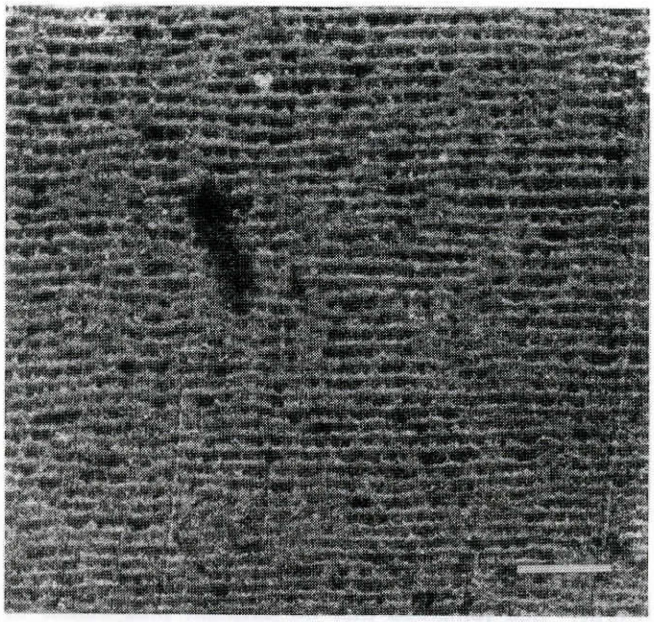

Figure 6. TEM photograph of the paradermal section through an iridosome of a rudraksha fruit. Note the linear arrangement of the thin layers, suggesting a three-dimensional orientation. Bar indicates 1 μm.

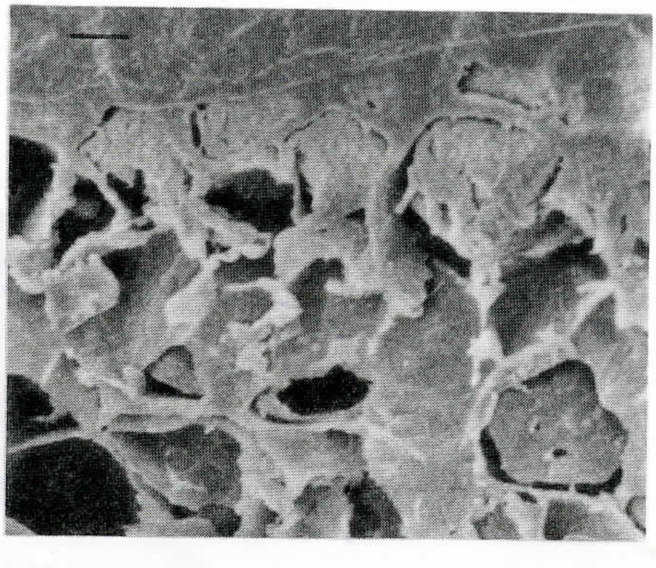

Figure 7. SEM photograph of a freeze-tractured portion of the epidermal and cuticular layer of a rudraksha fruit. Note the presence of partially-sectioned structures (iridosomes) just beneath the adaxial walls of the epidermal cells. Bar indicates 5 μm.

structure is apparently assembled between the plasmalemma and the outer wall of the epidermal cells (Figure 5).

The function of iridescence

Fruit colour is generally regarded as an adaptation to promote dispersal by animals, particularly birds. The brilliant blue of rudraksha fruits may increase their visibility to the large birds that consume and disperse them. An advantage of structural coloration is that the colours are less affected by the fruit ripening, and may last longer. Ripe rudraksha fruits fall to the ground; the colour persists even after the cortex decays; and the persistent colour may attract frugivore dispersers. In iridescent blue leaves, colour is strongly associated with extreme shade of the understory of tropical rainforests[13], although the physiological mechanism still is a puzzle. In these filters constructive interference at 1/2 thickness is accompanied by destructive interference at 1/4 filter thickness. For instance, constructive interference at 439 nm would mean effective penetration of light above approximately 550 nm. Lee and Lowry[14] hypothesized that destructive interference could result in reduced reflection at longer wavelengths, promoting increased photosynthetic efficiency. In rudraksha the greater reflectance at shorter wavelengths means the strong colour production is associated with transparency in the longer wavelengths of photosynthetically active radiation, and these fruits could fix carbon through photosynthesis even when colourful and ripe. Photosynthesis in green and unripe fruits contributes significantly to the carbon balance of many plants[22,23]. However, in ripe fruits, the colours are mostly produced by anthocyanin pigments. These absorb all wavelengths except red or blue wavelengths, and the backscatter from unpigmented internal tissues produces the colour. The partially transparent cell walls of rudraksha fruits allow light to penetrate into the chlorophyllous cortex tissue (Figure 3). A test of this hypothesis is to measure differences in carbon dioxide flux by the fruits in darkness compared to light. Rudraksha fruits did release less CO_2 in shady conditions similar to the understory than in total darkness. These differences may be greater in higher light conditions, but elevated fruit temperatures would increase respiration and make the comparison difficult[11].

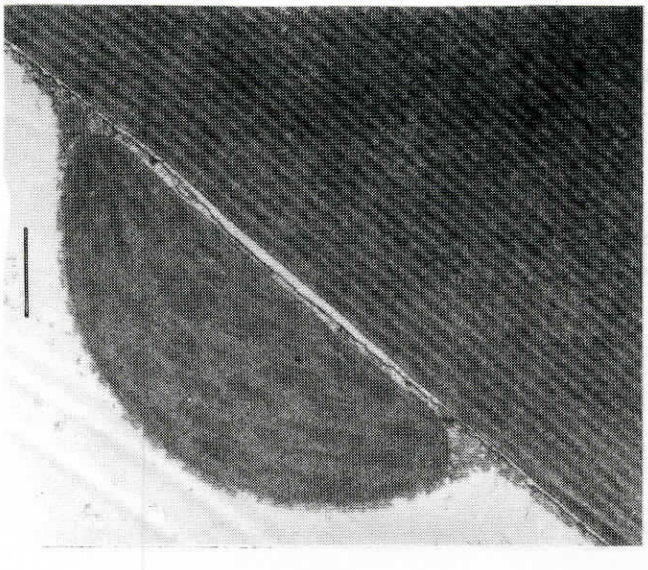

Figure 8. TEM photograph of the transverse section of an adaxial epidermal cell wall of an iridescent blue leaf of *Danaea nodosa*[16]. Note the distinct helicoidal thickenings in the upper portion of the wall. These were of a smaller thickness in green leaves. Bar indicates 1 µm.

Future research

Although iridescent blue colour production is most striking in the fruits of rudraksha, blue fruit colour is prevalent in *Elaeocarpus* throughout its distribution. An earlier survey of more than 25 blue-fruited taxa from other families had not revealed additional iridescent taxa (unpublished research). A more careful survey may reveal new taxa with blue or other colour iridescent fruits. In such fruits blue colour would not be associated with modified anthocyanins, easily extractable with acidified methanol, and the colour would be present well after the senescence of the fruits. Fruits of *Dealarbrea michaeana* (Araliaceae) and the blue arils of *Ravenala madagascarensis* (Musaceae) fit these requirements and may also produce colour via constructive interference (unpublished research). A comparative study of the basis for colour production in *Elaeocarpus*, coupled with a phylogeny based on molecular and morphological data, may help us understand how this phenomenon evolved. Iridescent blue-fruited taxa in other families (as the Araliaceae) could be the out-groups in such an evolutionary analysis.

In classical cultures throughout the world the medicinal and sacred values of plants are frequently associated

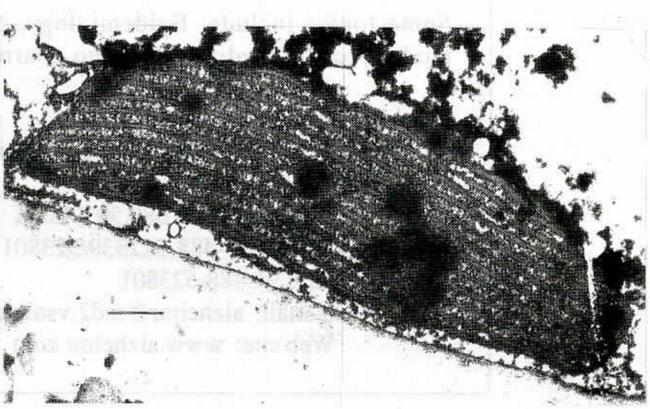

Figure 9. TEM photograph of the transverse section of an adaxial epidermal cell of an iridescent blue leaf of *Phyllagathis rotundifolia*[17].

with the remarkable appearance of the plant, what is generally known as 'the doctrine of signatures'. For instance, the medicinal benefits of the ginseng and mandrake plants are suggested by the limb-like lateral roots[24]. It is tempting to speculate that the cultural (i.e. spiritual) significance of rudraksha fruits is associated with the striking blue colour of the wall. Since they are particularly associated with the worship of Siva, 'the blue-throated one', perhaps the fruit colour helps explain the selection of the stony endocarp. Iridescent blue and green peacock feathers also have symbolic importance. Yet, blue may be a less important symbolic colour than red, and it is unlikely that many wearers of the beads had been aware of the blue fleshy exocarp, since the beads were collected and processed in remote regions and transported through trade. Perhaps careful analysis of classical Sanskrit texts may reveal more about the origin of use of this fruit. More research will certainly reveal clues to the origin of its remarkable colour.

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