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The green colour of vegetation

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The blue of the sky and the green of vegetation are the colours exhibited by the face of nature with which we are all most familiar, one due to the atmosphere of the earth lit up by the rays of the sun and the other to the leaves of plants growing under the beneficent influence of those same rays. Like the colours of the sky, the colours of vegetation show a great range of variation alike in respect of their luminosity and their hue. They are of the deepest interest to us, for they are the symbols of life on the surface of our planet without which it would be a dead world. Quite naturally, therefore, the origin of those colours might well be expected to be a thoroughly understood subject. Remarkably enough, this is not so and it might justly be said that the reason why grass looks green to us is far from being familiar knowledge.

Even the thinnest of leaves when held up in sunlight does not permit of the sun's disk being seen through it. In other words, the incident light is completely diffused or scattered besides suffering absorption within the material. It is very commonly the case that the upper and lower surfaces of a leaf present a very different appearance. The former exhibit in diffuse daylight a deeper colour and are also smoother. In consequence, when held at the proper angle to a beam of light incident on it, there is an observable reflection or glitter at the surface. On the other hand, the colour of the lower surface appears diluted by admixture with white light and by reason of its roughness, the regular reflection by the surface is weakened and may indeed not be noticeable at all. In the circumstances stated above, we have two distinct and alternative methods of studying the colour of green leaves. The first is to observe the *upper* surface of the leaf holding it towards the light in such position and viewing it at such an angle that the surface reflection or glitter is unobservable and only the light emerging from the interior of the leaf is seen. The second method is to observe the light which emerges *through* the leaf when it is held up against the source of light. In the latter case, the slit of the observing spectroscope may be brought up close to the leaf. It then makes no difference which side of the leaf faces the source of light. In either case, it is desirable to use a powerful source of illumination.

It has long been known that the pigments universally present in green leaves are of two sorts and their chemical constitution has been ascertained by appropriate methods of investigation. They are respectively the carotenoids and the chlorophylls. When sunlight falls upon a leaf and before it can emerge again from its interior, it suffers both diffusion and absorption. It is the remnant that survives these processes which we perceive, though it should not be forgotten that in many cases, reflection and diffusion at the exterior surfaces of leaves also play an important role in determining their appearance to an observer. If we lay aside the latter complication, we may say that the perceived colour is determined principally by the extinction of the sun's rays in their passage through the material of the leaf produced by the pigments referred to above. It is well known also that the carotenoids exercise a powerful absorption of the blue and violet regions of the spectrum. Such absorption is amply sufficient to account for the fact that very little of the wavelength range between 400 and 500 mμ gets through a green leaf, as may be readily verified by holding it up against the bright sky and viewing the light which filters through with a pocket spectroscope. Even with tender leaves which exhibit a greenish-yellow hue, the blue and violet of the spectrum come through only feebly, while in the case of the thicker and more mature leaves which appear of a full green colour, the extinction of the violet and blue is complete and extends also into the green up to 520 mμ. The two species of chlorophyll respectively labelled as (*a*) and (*b*) which are present in green leaves exhibit a powerful absorption in the vicinity of the red end of the spectrum, the peak of chlorophyll (*a*), according to the observations which have been made with the material in an ether solution, appearing at about 660 mμ and that of chlorophyll (*b*) at about 640 mμ. By holding up a green leaf against direct sunlight, and viewing the light emerging through it with a pocket spectroscope, it is possible to observe the absorption bands due to the chlorophylls appearing in the extreme red.

When we seek to understand or explain the colour of green leaves observed in these circumstances, it is necessary to remember that the luminous efficiency of monochromatic light varies enormously over the range of the visible spectrum. It is very small near the violet end of the spectrum, rises progressively and reaches a maximum at about 560 mμ and then drops down again at longer wavelengths. At 640 mμ, it is only about 20% of its value at 560 mμ, while at 660 mμ, it is only about 10% and at 680 mμ, it is very small. It is clear from these figures that the major chlorophyll absorptions appear in a region of which the luminous efficiency is already small. It follows that they could have no great influence on the visually perceived effect of the light that comes through, either in respect of the luminosity or in respect of its hue. It is known also that chlorophylls have a powerful absorption in the wavelength range between 400 and 500 mμ. But this is the range in which the absorption by the carotenoids is also effective. The effect of the chlorophylls would therefore merge into it and need not be separately considered in the present context.

Thus, the observed colour of a leaf would be determined by its spectroscopic behaviour in the wavelength range between 500 and 640 mμ in which region neither the carotenoids nor the chlorophylls have any major absorptive effects. What the colour exhibited to our vision by this range of wavelengths would be—

in the absence of any specified absorption within that range—can be readily ascertained in a variety of ways. We may, for instance, simply view the sky through a colour filter which cuts out the whole of the spectrum up to 520 mμ and lets through all greater wavelengths. The light transmitted by such a filter appears of a golden-yellow hue. There are several alternative procedures which yield the same observable result, viz., a golden-yellow colour. For example, we may use the petals of any flower which exhibits that hue and find that the light which filters through it has the same or nearly the same spectral composition. Many croton leaves exhibit (at least in some areas) a golden-yellow hue. Likewise, green leaves which have passed the stage of maturity and are about to drop off the tree usually exhibit a golden-yellow colour. Any of these cases can serve as a standard of comparison with the spectrum of green leaves in various stages of maturity.

When such comparisons are made, a surprising result emerges, viz., that the spectrum of the light emerging through a green leaf bears a close resemblance to that observed in the transmission through a flower or a leaf exhibiting a golden-yellow hue. Indeed, at first sight, it is not easy to discover what the difference in spectral composition are which give rise to the observed differences in the perceived colour. A critical examination of the transmission spectra of leaves in various stages of maturity however discloses that in the spectrum of the green leaf, the yellow sector of the spectrum between 570 and 590 mμ is weakened. The weakening is just discernible with immature leaves which exhibit a greenish-yellow hue. It is easily seen in the case of mature leaves which exhibit a bright green colour. Leaves whose colour is a dark green show the absorption band between 570 and 590 mμ conspicuously, the green and orange-red sectors of the spectrum which lie on either side then appearing well separated from each other. As we proceed from stage to stage in the development of the leaf towards maturity, the total quantity of light which finds its way through the leaf also progressively diminishes. Both the green and the orange-red sectors of the spectrum, however, continue to be visible with comparable intensities. But the intensity of the orange-red sectors relatively to that of the green sector shows an observable and progressive diminution.

From these observations, it becomes clear that the colour differences observed between a green leaf and a golden-yellow flower are the result of the absorption of the yellow sector of the spectrum between 570 and 590 mμ in the green leaf. As this absorption progressively increases, the colour changes from a greenish-yellow to a bright green and finally to a dark green. Further, since the orange-red sector of the spectrum is conspicuously visible even in the case of mature green leaves whose colour does not exhibit the slightest hint of any yellowish tinge, we are obliged to conclude that as the yellow sector between 570 and 590 mμ which is the connecting link between the green and the orange-red sector is weakened, the effect of the orange-red is masked or suppressed, in other words, prevented from entering into the range of perception, by reason of the presence of the more luminous green sector.

Owing to the non-uniformity of the photographic sensitivity of the commercially available panchromatic films in the region of the spectrum with which we are here concerned, it is not easy to obtain and present an objective demonstration of the facts of observation described above in the form of recorded spectra. After some discouraging failures, however, a fair measure of success has been achieved using the special "Agfa Raman plates" which have been developed by a well known firm of manufacturers.

Five spectrograms appear in figure 1 here reproduced. Of these, the second and the fourth, figure 1(b) and (d), are the spectra of the light source employed when covered with a golden-yellow filter. In these pictures, the left half of the spectrum

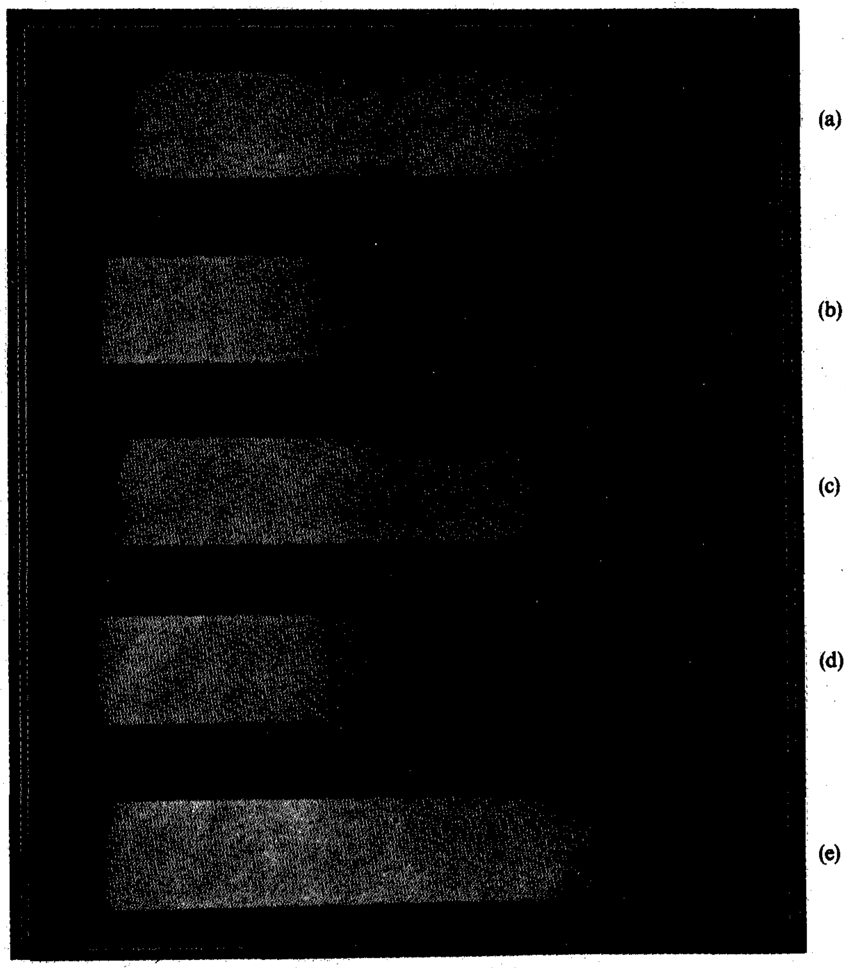

Figure 1. Spectroscopic comparison of green leaves and a yellow colour-filter. (a), (c) and (e), Green leaves; (b) and (d), colour-filter.

exhibiting the red and orange sectors appears much brighter than the right half which is the green sector. This is due to the difference in photographic sensitivity for these regions. It does not, however, prevent the effect under consideration, viz., the absorption in the yellow by the green leaves being exhibited in three other spectrograms, viz., figure 1(a), (c) and (e). They were recorded with three croton leaves, which were respectively a very dark green, a bright green and a greenish-yellow in colour. Figure 1(a) exhibits the absorption band in the yellow quite clearly. But it is much less clear in figure 1(c) and can scarcely be made out in figure 1(e).

Figure 1 also exhibits the other effects mentioned. In all the three cases studied, the red and the orange parts of the spectrum come through and their intensities are seen to be comparable with those of the green sector. We should, however, take note of the difference in photographic sensitivities for these regions. When due allowance is made for this, it is seen that the red-orange sector is weaker relatively to the green in the darker-coloured leaves.

We may sum up the results of the study by the statement that it is the absorption of the *yellow* of the spectrum and not the absorption of the red that is responsible for the observed green colour of leaves. That the absorption band in the yellow is not noticeable in the case of leaves which have turned yellow before dropping off is an indication that chlorophyll is responsible for its presence, either by itself or in association with the carotenoid pigments.

The extraordinary role played by the yellow sector of the spectrum in the case of the green leaves does not stand by itself. Indeed, in a forthcoming memoir by the author which will shortly appear in the *Proceedings of the Indian Academy of Sciences*, it is shown to be a very general feature. That the masking of the weaker by a stronger sensation is also a general feature has been recorded in that memoir.