Plant Physiol. (1973) *52*, 57–62

Optical Parameters of Leaves of 30 Plant Species[1]

Received for publication January 22, 1973

H. W. GAUSMAN AND W. A. ALLEN
Southern Region, Soil, Water, and Air Sciences, Agricultural Research Service, United States Department of Agriculture, Weslaco, Texas 78596

ABSTRACT

Optical parameters (absorption coefficient *k*, infinite reflectance R_∞, scattering coefficient *s*) are tabulated for seven wavelengths and analyzed for statistical differences for 30 plant species. The wavelengths are: 550 nm (green reflectance peak), 650 nm (chlorophyll absorption band), 850 nm (infrared reflectance plateau), 1450 nm (water absorption band), 1650 nm (reflectance peak following water absorption band at 1450 nm), 1950 nm (water absorption band), and 2200 nm (reflectance peak following water absorption band at 1950 nm).

Thick, complex dorsiventral (bifacial mesophyll) leaves such as rubber plant, begonia, sedum, and privet had lower R_∞ values than thinner, less complex dorsiventral leaves (*i.e.*, soybean, peach, bean, rose) or essentially centric (undifferentiated mesophyll) sorghum and corn leaves. Infinite reflectance was negatively correlated with leaf thickness (−0.734).**

Thick, complex dorsiventral leaves (crinum, oleander, privet, rubber plant, sedum) had higher (*p* 0.01) *k* values than thinner, less complex dorsiventral leaves (*i.e.*, soybean, rose, peach) or essentially centric sorghum, sugarcane, and corn leaves. A coefficient of 0.718 was obtained for the correlation of *k* values with leaf thickness values.**

Complex dorsiventral oleander, orange, and crinum leaves had higher (*p* 0.01) *s* values than less complex dorsiventral (*i.e.*, onion, begonia, banana) or centric leaves (*i.e.*, corn and sugarcane). The scattering coefficient was not correlated with leaf thickness.

Reflectance and transmittance of a plant leaf have been explained on the basis of critical reflection of light at the cell wall-air interface of the spongy mesophyll tissue (22). A hypothesis has been advanced that leaf reflectance derives from the diffuse characteristics of plant cell walls (19). Light reflectance from a leaf is generally reduced over all wavelengths when the leaf is infiltrated with water (14, 16) or with an oil mixture (23). Most of the reflectance, therefore, originates internally and is reduced when the cell wall-air interfaces are eliminated. Reflectance at 680 and 1950 nm is relatively unchanged by infiltrations, however, so most of it must originate from the cuticle or surface of the leaf. The structure of light beams reflected from plant leaves has also been studied (17).

Near infrared light reflectance (750–1350 nm) usually increases with an increase in number of intercellular air spaces (7, 8) because light is scattered in passing from hydrated cell walls with a refractive index of 1.47 (23) to intercellular air with a refractive index of 1.0. For example, maturation of a cotton leaf is characterized by development of intercellular air spaces in the mesophyll; consequently light reflectance increases and light transmittance of the leaf decreases (8). Internal refractive index discontinuities other than air-cell interfaces are responsible for some of the near infrared light reflected by a leaf (6, 19, 23).

Diffuse reflectance and transmittance of a compact leaf such as corn, a leaf impregnated with water, and an immature cotton leaf immediately after it unfolds (9) can be predicted from a plate theory (4). Generalization of the plate theory (flat plate model) to include the effect of intercellular air spaces (4) leads to the concept of void area index of a leaf. When a leaf is regarded as a pile of *N* compact layers separated by infinitesimal air spaces, the VAI[2] is given as *N*-1. The VAI of a compact leaf is zero. The VAI is roughly the average number of air spaces penetrated by a ray passing through the leaf. Parameters that emerge from the flat plate theory (1, 13) include a measure of the water and air in the leaf and the effective index of refraction *n* and absorption coefficient *k* (3–5, 8, 9). The effective index of refraction of a typical leaf is not inconsistent with the refractive index of epicuticular wax. The effective absorption coefficient of a typical leaf is a superposition of the absorption coefficients of chlorophyll and pure liquid water. The plate model of a leaf is used to determine moisture content from reflectance and transmittance measurements. The absorption of a compact leaf can be simulated closely over the 1350- to 2500-nm wavelength interval by absorption of an equivalent water thickness.

Reflectance against a soil background increases as number of leaf layers in the plant canopy increases until a stable value of reflectance called infinite reflectance R_∞ is attained (1). In the visible and in the 1500- to 2500-nm WLI, R_∞ is reached when plants reach a leaf area index (LAI) of 2. Leaf area index is the cumulative one-sided leaf area per unit ground area measured from the canopy top to a plane at a given distance above ground (15). In the 750- to 1350-nm WLI, a LAI of about 8 is required to reach R_∞ because of the transparency of the leaves (4). Infinite reflectance can be calculated if the reflectance and transmittance of a single leaf are known.

The experimental and theoretical spectral reflectance and transmittance from two, four, six, and eight stacked leaves

[1] This study was supported in part by the National Aeronautics and Space Administration under Contract No. R-09-038-002.

** Significance of the correlation coefficient for the 0.01 level of significance.

[2] Abbreviations: VAI: void area index; WLI: wavelength interval; LAI: leaf area index.

have been presented (1, 15). In the 750- to 1350-nm WLI, plant leaves absorb very little electromagnetic radiation. The leaf reflects about half and transmits the other half of the incident solar radiation in this interval to leaves lower in the plant canopy (21). Multiple transmission and reflection from leaves in a plant canopy result in a maximum reflectance of about 40% of the energy incident on a mature crop canopy in the 750- to 1350-nm WLI.

The purpose of this study is to present significant differences among optical parameters (absorption coefficient k, infinite reflectance R_∞, scattering coefficient s) for 30 plant species at the 550 nm (green reflectance peak), 650 nm (chlorophyll absorption band), 850 nm (on infrared reflectance plateau), 1450 nm (water absorption band), 1650 nm (reflectance peak following water absorption band at 1450 nm), 1950 nm (water absorption band), and 2200 nm (reflectance peak following water absorption band at 1950 nm) wavelengths. The optical constants can be used to predict the response of a leaf to radiation. These constants are valuable for researchers doing light-canopy and photosynthesis studies.

MATERIALS AND METHODS

Ten fully grown and healthy appearing leaves were harvested from each of 30 plant species listed in Table I. All plants were field-grown, except that lettuce and onions were purchased in a fresh condition at a local market, and soybeans and pinto beans were grown in a greenhouse. Immediately after excision, leaves were wrapped in Saran[3] or Glad-Wrap to minimize moisture loss. Leaves were wiped with a slightly dampened cloth preceding spectrophotometric measurements to remove surface contaminants. Only one-half (split longitudinally) of the tubular onion leaf was used for spectrophotometric measurements.

Table I. *Common and Latin Names of 30 Plant Species Used in This Study*

Common Name	Latin Name
Avocado	*Persea americana* Mill.
Banana	*Musa paradisiaca* L.
Bean	*Phaseolus vulgaris* L.
Begonia	*Begonia semperflorens* Link and Otto
Cantaloupe	*Cucumis melo* L. var. *reticulatus* Naud.
Corn	*Zea mays* L.
Cotton	*Gossypium hirsutum* L.
Crinum	*Crinum fimbriatulum* Baker
Eucalyptus	*Eucalyptus camaldulensis* Dehnh
Rubber plant	*Ficus elastica* Roxb.
Hyacinth	*Eichhornia crassipes* (Mart.) Solms
Lettuce	*Lactuca sativa* L.
Privet	*Ligustrum lucidum* Ait.
Okra	*Hibiscus esculentus* L.
Oleander	*Nerium oleander* L.
Onion	*Allium cepa* L.
Orange	*Citrus sinensis* (L.) Osbeck
Peach	*Prunus persica* (L.) Batsch
Pepper	*Capsicum annuum* L. and other spp.
Pigweed	*Amaranthus retroflexus* L.
Pumpkin	*Cucurbita pepo* L.
Rose	*Rosa* L. (var. unknown)
Sedum	*Sedum spectabile* Boreau
Sorghum	*Sorghum bicolor* (L.) Moench
Soybean	*Glycine max* (L.) Merr.
Sugarcane	*Saccharum officinarum* L.
Sunflower	*Helianthus annuus* L.
Tomato	*Lycopersicon esculentum* Mill.
Watermelon	*Citrullus lanatus* (Thunb.) Mansf.
Wheat	*Triticum aestivum* L.

A Beckman Model DK-2A spectrophotometer, equipped with a reflectance attachment, was used to measure spectral diffuse reflectance and transmittance on the adaxial (upper) surface of single leaves. Data were recorded at discrete 50-nm intervals over the continuously measured 500- to 2500-nm WLI. The basic design of the instrument allows illumination of the leaf surface with a beam of monochromatic light of a desired wavelength. The reflected or transmitted light is collected by an integrating sphere, and the intensity is measured by a photoelectric cell. The integrating sphere is coated with a nearly perfect diffusive reflector of light. When an elementary area of the sphere is illuminated with light, the diffusing material reflects the light, omnidirectionally, to other parts of the sphere. A detector in the sphere surface measures the amount of light being reflected in the sphere.

Data have been corrected for decay of the MgO standard (18) to give absolute radiometric data (2).

Leaf thickness was measured with a linear transducer and digital voltmeter (12). Percentage of leaf water content was determined on an oven-dry weight basis by drying leaves at 68 C for 72 hr and cooling in a desiccator before final weighing. Leaf thickness and water content determinations were not made on wheat leaves.

Leaf thickness and diffuse reflectance and transmittance measurements were completed within 6 hr, after leaves were obtained for each species.

Infinite reflectance R_∞ and the absorption k and scattering s coefficients were calculated by the methods of Allen and Richardson (1). Equations used were

$$R_\infty = 1/a \tag{1}$$

$$k = [(a-1)/(a+1)] \log b \tag{2}$$

$$s = [2a/(a^2-1)] \log b \tag{3}$$

$$a = (1 + r^2 - t^2 + \Delta)/2r \tag{4}$$

$$b = (1 - r^2 + t^2 + \Delta)/2t \tag{5}$$

R_∞ = infinite reflectance, t = transmittance, k = absorption coefficient, a = optical constant, s = scattering coefficient, b = optical constant, r = reflectance. The quantity Δ is defined by the relation

$$\Delta^2 = (1 + r + t)(1 + r - t)(1 - r + t)(1 - r - t) \tag{6}$$

The quantities a and b (equations 4 and 5) are constants at a given wavelength. Since r and t vary with wavelength, the quantities a and b are also functions of wavelength. Light passing through a leaf model is absorbed and scattered in direct proportion to a nondimensional differential distance, dn, traversed and in direct proportion to the amplitude of the light at that point. The quantity n is the leaf area index. Absorbed radiation disappears from the model. Scattered radiation is merely changed in direction. Since the model is one-dimensional, the scattering must be either forward or backward. The forward scattered component is indistinguishable from the incident light but the backward scattered compo-

[3] Trade and company names are for the convenience of the reader and do not imply endorsement or preferential treatment by the United States Department of Agriculture.

nent adjoins the light moving in the opposite direction. The absorption coefficient k (equation 2) and the scattering coefficient s (equation 3) are associated with the leaf area index. The coefficients s and k correspond to fractions of light which are scattered and absorbed respectively per unit of leaf area index.

Variance analysis and Tukey's w procedure (20) were used on the spectrophotometric data for the selected wavelengths at 550-, 650-, 850-, 1450-, 1650-, 1950-, and 2200-nm wavelengths.

RESULTS AND DISCUSSION

Leaf Thickness and Water Content. Table II gives leaf thicknesses and water contents for 29 plant species (data unavailable for wheat). Table II is included to show the wide range of leaf thickness (0.140–0.978 mm) and water content (60.1–97.0%) values represented by the plant species. These data are used for descriptive and correlative purposes. The optical parameters (infinite reflectance R_∞, absorption coefficient k, and scattering coefficient s) represent the optical differences among leaves of the plant species.

Infinite Reflectance R_∞. Table III contains infinite reflectances R_∞ for 30 plant species at seven wavelengths of light. The interaction of plant species with the wavelengths was highly significant (p 0.01). The significant variance was primarily caused by low R_∞ values of onion, sedum, and lettuce at the 1650-nm wavelength; and high R_∞ values of lettuce at the 550 and 650 nm, of bean at the 850 nm, and of peach and sorghum at the 1950-nm wavelengths. Lettuce was considerably different from the other species in the visible region because its leaves were pale green (low chlorophyll content) and, hence, very transparent. The application of Tukey's w procedure to the means of the seven wavelengths for each species divides the 30 species into many significantly different groups with like means within each group. However, thick (Table II), complex dorsiventral (bifacial mesophyll) leaves such as those of rubber plant, begonia, sedum, and privet generally had lower R_∞ values than thinner, less complex dorsiventral leaves (*i.e.*, soybean, peach, bean, rose) or essentially centric (undifferentiated mesophyll) sorghum and corn leaves. Sorghum leaves had significantly higher average R_∞ values than leaves of all other species. This indicates that sorghum leaves had a finer divided mesophyll structure than leaves of the other species that was conducive to short path lengths of light and subsequently less light absorptance (5). Coefficients for the linear correlations of R_∞ values with k values for the 30 species were −0.654**, −0.613**, −0.837**, −0.802**, −0.899**, −0.819**, and −0.861** for the 550-, 650-, 850-, 1450-, 1650-, 1950-, and 2200-nm wavelengths, respectively. Considering the means of all wavelengths, R_∞ was negatively correlated with leaf thickness (−0.734**).

Absorption Coefficient k. Table IV shows the absorption coefficients k for 30 plant species at the seven wavelengths of light. The interaction of plant species with wavelengths was highly significant (p 0.01). The significant variance was pri-

Table II. *Leaf Thickness and Water Content of Leaves for 29 Plant Species (Data Unavailable for Wheat) Arranged in Descending Order of Magnitude*

Plant	Leaf Thickness	Plant	Water Content
	mm		%
Onion	0.978	Lettuce	97.0
Sedum	0.816	Sedum	94.9
Lettuce	0.720	Begonia	94.8
Crinum	0.665	Onion	93.5
Rubber plant	0.606	Bean	93.5
Privet	0.527	Crinum	90.1
Begonia	0.468	Banana	87.7
Cantaloupe	0.468	Hyacinth	86.9
Oleander	0.442	Cantaloupe	85.8
Sunflower	0.407	Pepper	85.0
Hyacinth	0.375	Tomato	83.4
Sorghum	0.274	Watermelon	82.4
Eucalyptus	0.272	Cotton	81.7
Bean	0.263	Pigweed	81.7
Tomato	0.262	Soybean	81.4
Avocado	0.255	Okra	80.6
Sugarcane	0.248	Pumpkin	78.0
Orange	0.245	Sunflower	76.9
Banana	0.241	Rubber plant	75.8
Watermelon	0.232	Sorghum	74.9
Cotton	0.209	Corn	74.8
Pepper	0.203	Sugarcane	72.4
Corn	0.200	Rose	70.6
Okra	0.198	Oleander	68.4
Pigweed	0.170	Privet	66.6
Pumpkin	0.157	Peach	65.8
Peach	0.152	Orange	63.7
Rose	0.150	Avocado	60.6
Soybean	0.140	Eucalyptus	60.1
Mean	0.357		79.6
SD	0.219		10.6

Table III. *Infinite Reflectance R_∞ of 30 Plant Species at Seven Wavelengths of Light*

Plant	Wavelength							Mean[1]
	550	650	850	1450	1650	1950	2200	
	nm							
Onion	12.0	8.2	71.2	6.8	18.7	4.4	8.1	18.5 a
Rubber plant	8.1	5.1	74.0	7.8	27.3	3.7	10.3	19.5 ab
Begonia	13.2	6.6	77.3	6.2	24.2	3.9	8.6	20.0 ab
Sedum	20.4	8.4	78.1	5.2	18.8	3.3	6.3	20.1 b
Privet	10.3	5.4	74.0	9.0	29.2	4.1	11.2	20.5 bc
Oleander	10.8	6.8	67.1	13.0	34.4	5.5	16.3	22.0 cd
Crinum	15.8	7.2	74.4	10.0	30.5	5.3	13.7	22.4 d
Banana	10.7	6.0	73.9	12.3	35.9	5.1	17.3	23.0 de
Hyacinth	12.1	7.0	75.4	11.8	35.0	4.8	15.7	23.1 de
Tomato	11.0	8.6	68.7	14.6	36.8	6.0	18.0	23.4 def
Eucalyptus	12.8	9.2	71.8	16.6	35.6	7.0	16.5	24.2 efg
Sunflower	11.1	8.5	75.2	14.6	37.0	6.5	17.0	24.3 efgh
Lettuce	40.2	27.6	63.0	9.1	18.7	5.6	9.7	24.8 fgh
Sugarcane	19.0	11.5	69.8	14.9	36.5	6.3	17.6	25.1 ghi
Cantaloupe	12.8	9.9	75.5	15.0	37.7	6.9	18.4	25.2 ghi
Cotton	12.0	7.7	75.9	15.9	39.8	6.0	19.3	25.2 ghi
Watermelon	14.6	9.9	70.3	17.2	40.1	7.0	20.3	25.6 ghij
Avocado	8.9	7.3	74.9	20.0	40.9	7.6	21.0	25.8 hij
Pigweed	12.5	9.0	78.6	16.5	41.2	5.8	19.9	26.2 ijk
Okra	13.1	9.2	74.9	18.9	42.8	7.0	22.0	26.8 jk
Pumpkin	11.9	8.7	73.3	20.2	44.1	7.5	23.1	27.0 jk
Corn	16.4	9.3	77.5	17.6	41.9	7.2	21.9	27.4 kl
Orange	10.2	7.1	75.0	22.7	44.7	8.6	24.5	27.5 kl
Wheat	13.5	7.7	75.5	22.6	45.7	9.0	26.2	28.6 l
Pepper	17.1	9.3	83.3	18.2	44.5	6.7	23.1	28.9 lm
Rose	10.6	7.3	81.1	25.2	50.0	9.7	29.1	30.4 mn
Bean	18.8	10.7	86.9	18.7	47.0	6.1	25.0	30.5 n
Peach	10.9	8.7	78.4	26.2	50.4	10.7	29.0	30.6 n
Soybean	13.5	7.9	80.3	24.0	51.0	8.3	29.5	30.6 n
Sorghum	17.4	11.3	77.3	27.1	50.8	12.3	30.2	32.3 o
Mean	14.1	8.9	75.1	15.9	37.7	6.6	19.0	
SD	5.8	3.9	4.7	6.1	9.4	2.1	6.7	

[1] Means followed by a common letter are not significantly different, p 0.01, according to Tukey's w procedure.

Table IV. *Absorption Coefficients k of 30 Plant Species at Seven Wavelengths of Light*

Plant	Wavelength							Mean[1]
	550	650	850	1450	1650	1950	2200	
				nm				
Soybean	1.408	2.483	0.023	0.749	0.179	1.875	0.500	1.031 a
Sorghum	1.697	3.139	0.033	0.690	0.184	1.649	0.493	1.126 ab
Rose	1.911	3.327	0.025	0.744	0.203	1.823	0.554	1.227 bc
Peach	2.234	3.004	0.032	0.747	0.208	1.827	0.579	1.233 bc
Pumpkin	1.863	2.932	0.046	0.945	0.260	2.216	0.694	1.279 bc
Okra	1.746	2.652	0.044	1.106	0.313	2.594	0.810	1.324 cd
Pigweed	1.831	3.025	0.027	1.034	0.280	2.392	0.735	1.332 cd
Cotton	1.587	2.716	0.036	1.168	0.332	2.762	0.847	1.350 cde
Sugarcane	1.423	2.553	0.064	1.286	0.390	2.862	0.953	1.362 cde
Pepper	1.461	2.904	0.022	1.213	0.306	2.879	0.822	1.372 cde
Watermelon	1.761	3.369	0.064	1.198	0.348	2.776	0.877	1.485 def
Bean	1.497	2.689	0.014	1.450	0.334	3.571	0.943	1.500 def
Eucalyptus	2.033	3.005	0.054	1.209	0.406	2.860	1.064	1.519 ef
Sunflower	1.917	2.515	0.042	1.401	0.402	3.340	1.070	1.527 ef
Corn	1.682	4.658	0.030	1.097	0.286	2.625	0.742	1.589 fg
Avocado	2.706	3.657	0.046	1.058	0.349	2.434	0.881	1.590 fg
Cantaloupe	1.890	3.076	0.040	1.463	0.397	3.424	1.032	1.617 fg
Lettuce	0.317	0.627	0.076	2.464	0.811	5.570	1.713	1.654 fg
Banana	1.701	4.413	0.039	1.379	0.366	3.390	0.911	1.743 gh
Wheat	2.227	5.286	0.048	1.050	0.304	2.528	0.792	1.748 gh
Tomato	2.352	4.241	0.077	1.561	0.451	3.666	1.112	1.923 h
Hyacinth	1.978	4.774	0.047	1.886	0.499	4.535	1.289	2.144 i
Orange	3.264	6.001	0.061	1.254	0.386	3.081	1.006	2.150 i
Begonia	1.425	3.043	0.031	2.441	0.670	6.399	1.658	2.238 i
Onion	1.308	2.311	0.043	2.870	0.845	6.328	1.968	2.239 i
Crinum	2.026	5.795	0.063	3.290	0.855	5.809	2.121	2.851 j
Oleander	3.930	6.028	0.120	2.425	0.708	5.216	1.773	2.886 j
Privet	2.656	6.196	0.065	2.655	0.801	6.360	1.992	2.961 j
Rubber plant	3.743	6.239	0.060	3.059	0.862	6.408	2.186	3.222 k
Sedum	1.490	5.008	0.037	5.861	1.301	6.414	3.212	3.332 k
Mean	1.969	3.722	0.047	1.691	0.468	3.654	1.178	
SD	0.726	1.409	0.021	1.078	2.895	1.610	0.629	

[1] Means followed by a common letter are not significantly different, p 0.01, according to Tukey's w procedure.

marily caused by low k values of sorghum at 2200 nm and of lettuce at 550 and 650 nms; and high k values of oleander at the 550 and 850 nm, or rubber plant at 550 nm, and of sedum at 1450, 1650, and 2200 nm. Lettuce leaves were low and oleander and rubber plant leaves were high in chlorophyll content. Sorghum leaves had a finer divided mesophyll structure than the oleander, sedum, and rubber plant leaves. As indicated previously, a finely divided mesophyll structure, compared with a coarsely divided structure is conducive to short path lengths of light within the mesophyll and subsequently there is less light absorption. This is also evident when comparisons are made with Tukey's w procedure (Table IV) among the means of the seven wavelengths for each species. Thick, complex dorsiventral leaves (crinum, oleander, privet, rubber plant, sedum) had significantly higher (p 0.01) k values than thinner, less complex dorsiventral leaves (*i.e.*, soybean, rose, peach) or essentially centric sorghum, sugarcane, and corn leaves (Table II).

The absorption coefficient k in the Kubelka-Munk representation (1) is a number that expresses the amount of water over the port of the spectrophotometer. If all leaves have the same water content, as is approximately true from Table II, then k must correlate well with leaf thickness. A coefficient of 0.718** was obtained for the correlation of absorption coefficients with leaf thicknesses.

Scattering Coefficient *s*. Table V shows the scattering coefficient s for 30 plant species at seven wavelengths of light. The interaction of plant species with wavelengths was highly significant (p 0.01). The significant variance was primarily caused by low s values of begonia at 1450-nm, of lettuce at 1650-nm, and of pigweed and soybean at 1950-nm wavelengths; and by high s values of corn at 650-nm, of orange at 1450-, 1650-, and 2200-nm, and of oleander at 550- and 850-nm wavelengths. Mean comparisons with Tukey's test show that complex dorsiventral oleander, orange, and crinum leaves had significantly higher (p 0.01) s values than less complex dorsiventral (*i.e.*, onion, begonia, banana) or centric leaves (*i.e.*, corn and sugarcane). Complex dorsiventral leaves have more air-cell interfaces than simpler dorsiventral leaves that are conducive to light scattering, particularly at the 850-nm wavelength (9, 10). The values of s were correlated with k values at the 650-nm wavelength (r 0.663**) and at the 1950-nm wavelength (r 0.590**). The 650- and 1950-nm wavelengths correspond to chlorophyll and water absorption bands, respectively. Coefficients of variation for the 650- and 1950-nm wavelengths were 17.6 and 24.6%, respectively. Values of s were also cor-

Table V. *Scattering Coefficients s of 30 Plant Species at Seven Wavelengths of Light*

Plant	Wavelength							Mean[1]
	550	650	850	1450	1650	1950	2200	
				nm				
Onion	0.407	0.449	0.716	0.452	0.476	0.615	0.378	0.499 a
Begonia	0.497	0.459	0.859	0.342	0.564	0.539	0.341	0.514 a
Banana	0.456	0.602	0.830	0.441	0.636	0.382	0.460	0.544 ab
Lettuce	0.633	0.586	0.662	0.535	0.446	0.703	0.397	0.566 bc
Pigweed	0.598	0.655	0.866	0.488	0.664	0.313	0.456	0.577 bcd
Cotton	0.493	0.491	0.943	0.523	0.726	0.374	0.501	0.579 bcd
Soybean	0.508	0.467	0.894	0.607	0.739	0.360	0.597	0.593 cd
Sunflower	0.541	0.511	0.954	0.561	0.747	0.501	0.528	0.620 de
Pumpkin	0.573	0.617	0.922	0.598	0.732	0.389	0.541	0.625 de
Eucalyptus	0.679	0.669	0.922	0.574	0.691	0.467	0.499	0.643 ef
Rose	0.506	0.565	0.985	0.670	0.810	0.431	0.640	0.658 efg
Sugarcane	0.818	0.749	0.968	0.528	0.706	0.408	0.492	0.667 efgh
Okra	0.604	0.595	1.033	0.629	0.811	0.418	0.581	0.667 efgh
Avocado	0.581	0.616	1.088	0.655	0.810	0.431	0.582	0.680 fghi
Cantaloupe	0.638	0.750	0.966	0.608	0.771	0.546	0.568	0.692 ghij
Watermelon	0.705	0.826	0.978	0.597	0.770	0.447	0.557	0.697 ghij
Hyacinth	0.614	0.770	1.072	0.577	0.829	0.482	0.575	0.703 ghijk
Corn	0.788	1.051	0.900	0.564	0.708	0.437	0.529	0.711 hijkl
Peach	0.615	0.623	1.025	0.719	0.851	0.489	0.662	0.712 hijkl
Pepper	0.719	0.655	1.099	0.656	0.881	0.442	0.642	0.728 ijkl
Tomato	0.652	0.871	1.065	0.624	0.827	0.498	0.594	0.733 jklm
Rubber plant	0.711	0.702	1.302	0.563	0.888	0.517	0.562	0.749 klmn
Sorghum	0.860	0.898	0.943	0.699	0.768	0.523	0.610	0.757 lmn
Privet	0.674	0.749	1.395	0.572	0.928	0.570	0.564	0.779 mn
Sedum	0.958	0.986	1.254	0.672	0.739	0.449	0.458	0.788 n
Wheat	0.800	0.949	1.166	0.784	0.943	0.547	0.757	0.849 o
Bean	0.850	0.726	1.331	0.819	1.110	0.490	0.834	0.880 o
Crinum	0.900	0.973	1.409	0.809	1.074	0.689	0.781	0.948 p
Orange	0.832	0.982	1.407	0.956	1.131	0.640	0.863	0.973 p
Oleander	1.007	0.938	1.476	0.824	1.129	0.645	0.814	0.976 p
Mean	0.674	0.716	1.047	0.622	0.797	0.558	0.578	
SD	0.154	0.176	0.210	0.128	0.169	0.098	0.137	

[1] Means followed by a common letter are not significantly different, p 0.01, according to Tukey's w procedure.

related with R_∞ at the 1450- (r 0.463**), 1650- (r 0.386**), and 2200- (r 0.519**) nm wavelengths. The scattering coefficient s is a function of the matter associated with a single leaf. If leaves of all plant species have essentially the same internal structure, the scattering coefficient should be strongly correlated with leaf thickness. However, this was not true (r 0.035), so it can be concluded that structure must play an important role in light scattering.

Acknowledgments—The laboratory and computer assistance of A. J. Richardson and D. E. Escobar are gratefully acknowledged.

LITERATURE CITED

1. ALLEN, W. A. AND A. J. RICHARDSON. 1968. Interaction of light with a plant canopy. J. Opt. Soc. Amer. 58: 1023-1028.
2. ALLEN, W. A. AND A. J. RICHARDSON. 1971. Calibration of a laboratory spectrophotometer for specular light by means of stacked glass plates. Rev. Sci. Instrum. 42: 1813-1817.
3. ALLEN, W. A., H. W. GAUSMAN, AND A. J. RICHARDSON. 1970. Mean effective optical constants of cotton leaves. J. Opt. Soc. Amer. 60: 542-547.
4. ALLEN, W. A., H. W. GAUSMAN, A. J. RICHARDSON, AND J. R. THOMAS. 1969. Interaction of isotropic light with a compact leaf. J. Opt. Soc. Amer. 59: 1376-1379.
5. ALLEN, W. A., H. W. GAUSMAN, A. J. RICHARDSON, AND C. L. WIEGAND. 1970. Mean effective optical constants of thirteen kinds of plant leaves. Appl. Opt. 9: 2573-2577.
6. GAUSMAN, H. W. 1973. Photomicrographic record of light reflected at 850 nanometers by cellular constituents of *Zebrina* leaf epidermis. Agron. J. 65: 504-505.
7. GAUSMAN, H. W., W. A. ALLEN, AND R. CARDENAS. 1969. Reflectance of cotton leaves and their structure. Remote Sens. Environ. 1: 19-22.
8. GAUSMAN, H. W., W. A. ALLEN, R. CARDENAS, AND A. J. RICHARDSON. 1970. Relation of light reflectance to histological and physical evaluations of cotton leaf maturity (*Gossypium hirsutum* L.). Appl. Opt. 9: 545-552.
9. GAUSMAN, H. W., W. A. ALLEN, V. I. MYERS, AND R. CARDENAS. 1969. Reflectance and internal structure of cotton leaves (*Gossypium hirsutum* L.). Agron. J. 61: 374-376.
10. GAUSMAN, H. W., W. A. ALLEN, M. L. SCHUPP, C. L. WIEGAND, D. E. ESCOBAR, AND R. R. RODRIGUEZ. 1970. Reflectance, transmittance, and absorptance of light of leaves for 11 plant genera with different leaf mesophyll arrangements. Texas A&M Univ. Tech. Monograph No. 7.
11. GAUSMAN, H. W., W. A. ALLEN, C. L. WIEGAND, D. E. ESCOBAR, R. R. RODRIGUEZ, AND A. J. RICHARDSON. 1971. The leaf mesophyll of twenty crops, their light spectra, and optical and geometrical parameters. SWC Research Report. 423, Weslaco, Texas.
12. HEILMAN, M. D., C. L. GONZALEZ, W. A. SWANSON, AND W. J. RIPPERT. 1968. Adaptation of a linear transducer for measuring leaf thickness. Agron. J. 60: 578-579.
13. KUBELKA, V. P. AND F. MUNK. 1931. Ein Beitrag zur Optik der Farbanstriche. Z. Tech. Physik. 11: 593-601.
14. MOSS, R. A. 1951. Absorption spectra of leaves. Ph.D. thesis. Iowa State University, Ames.
15. MYERS, V. I. AND W. A. ALLEN. 1968. Electrooptical remote sensing methods as nondestructive testing and measuring techniques in agriculture. Appl. Opt. 7: 1818-1838.
16. PEARMAN, G. I. 1966. The reflection of visible radiation from leaves of some western Australian species. Australian J. Biol. Sci. 19: 97-103.

17. RVACHEV, V. P. AND S. G. GUMINETSKIY. 1966. The structure of light beams reflected by the leaves of vegetation. Zhurnal Prikladnoy Spektroskopii (J. Appl. Spect.) 4: 415-421. (Translated by L. Heenan.)

18. SANDERS, C. L. AND E. E. K. MIDDLETON. 1953. The absolute diffuse reflectance of magnesium oxide in the near infrared. J. Opt. Soc. Amer. 43: 58.

19. SINCLAIR, T. R. 1968. Pathway of solar radiation through leaves. M.S. thesis. Purdue University, Lafayette, Ind.

20. STEEL, R. G. D. AND J. H. TORRIE. 1960. Principles and Procedures of Statistics. McGraw-Hill Book Co., Inc., New York.

21. WIEGAND, C. L., H. W. GAUSMAN, AND W. A. ALLEN. 1972. Physiological factors and optical parameters as bases of vegetation discrimination and stress analysis. Proc. Operational Remote Sensing, Am. Soc. of Photogrammetry, Falls Church, Va.

22. WILLSTÄTTER, R. AND A. STOLL. 1918. Untersuchungen über die Assimilation der Kohlensäure. Springer-Verlag, Berlin. p. 122.

23. WOOLLEY, J. T. 1971. Reflectance and transmittance of light by leaves. Plant Physiol. 47: 656-662.