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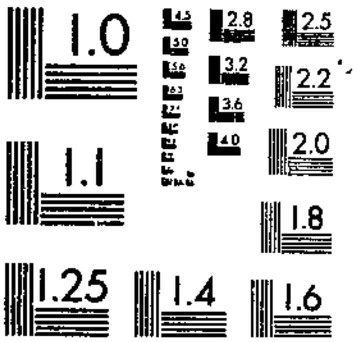

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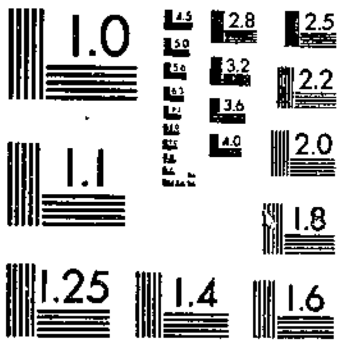

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A Revision of the Genus *Sennius* of North and Central America (Coleoptera: Bruchidae)

Technical Bulletin No. 1462

Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE
in cooperation with
Northern Arizona University

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The Leaf Mesophylls of Twenty Crops, Their Light Spectra, and Optical and Geometrical Parameters

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Contents

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The Leaf Mesophylls of Twenty Crops, Their Light Spectra, and Optical and Geometrical Parameters[1]

H. W. GAUSMAN, *plant physiologist;* W. A. ALLEN, *research physicist;* C. L. WIEGAND, *soil scientist;* D. E. ESCOBAR, *biological laboratory technician;* R. R. RODRIGUEZ, *physical science technician;* and A. J. RICHARDSON, *physicist, Southern Region Agricultural Research Service, United States Department of Agriculture*[2]

Summary

Leaf mesophylls among 20 agricultural crops are compared with: (1) Spectrophotometrically measured percent reflectances and transmittances, and calculated absorptances of the leaves over the 500- to 2,500-nanometer (nm.) wavelength interval, (2) percent leaf-water contents, (3) leaf thickness measurements, and (4) optical and geometrical leaf parameters. Data are given as averages of 10 leaves (replications) for each crop. The crops are: Avocado, bean, cantaloup, corn, cotton, lettuce, okra, onion, orange, peach, pepper, pigweed, pumpkin, sorghum, soybean, sugarcane, sunflower, tomato, watermelon, and wheat.

Thick, succulent lettuce leaves had the highest water content (97.0 percent), and dorsiventral avocado, orange, and peach, and compact sugarcane leaves had the lowest water contents (range 60.6 to 72.4 percent).

Soybean, peach, pumpkin, and pigweed leaves were thinnest (range 0.140 to 0.170 mm.) and sunflower, cantaloup, lettuce, and onion leaves were thickest (range 0.407 to 0.978 mm.).

Intensive study was given to the 550- and 1,000-nm. wavelengths, representing the visible (400 to 750 nm.) and near-infrared (750 to 1,350 nm.) spectral regions. Data for lettuce were omitted because the leaves sampled were immature.

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[1] The work was supported in part by the National Aeronautics and Space Administration under NASA Contract No. R-09-038-002, Current Code No. 160-75-01-07-10.

[2] The authors acknowledge the histological and technical assistance of Guadalupe Cardona, Marcia Schupp, and Ron Bowen. Thanks are extended to the Ansul Company Development Center, Weslaco, Tex., for supplying the bean and soybean plants.

The mean reflectance of the crop leaves at the 550-nm. wavelength was 13.3 ± 2.8 percent (one standard deviation). The majority of crops fell within the 13.3 ± 2.8 percent range, except avocado and orange (8.9 and 10.2 percent, respectively), and corn, pepper, sorghum, bean, and sugarcane leaves (16.2 to 18.6 percent).

At the 550-nm. wavelength, transmittances of orange, tomato, and avocado (1.9 to 5.5 percent) and okra, soybean, onion (14.8 to 18.8 percent) fell outside the 9.8 ± 4.2 percent range.

The mean absorptance for the crops at 550-nm. wavelength was 76.9 ± 5.8 percent. Thirteen crops fell within the 76.9 ± 5.8 percent range. Sugarcane, onion, bean, and pepper leaves with low absorptance (69.2 to 70.6 percent) and peach, tomato, avocado, and orange leaves with high absorptance (82.9 to 87.9 percent) fell outside the 76.9 ± 5.8 percent range. The leaves with high absorptance had well-differentiated dorsiventral mesophylls with many chloroplasts in their palisade cells. Leaves with low absorptance had poorly differentiated mesophylls—less distinction between palisade and spongy parenchyma cells.

The 1,000-nm. wavelength was used to evaluate the influence of leaf-mesophyll arrangement on near-infrared (750 to 1,350 nm.) light reflectance. The mean reflectance of the crop leaves at the 1,000-nm. wavelength was 48.0 ± 3.9 percent. The reflectance of onion (38.5 percent) and orange and bean (55.6 and 56.2 percent, respectively) fell outside this range. However, only one-half of the tubular onion leaf (split longitudinally) was used for spectrophotometric measurements. Thus, discounting onion as an unusual leaf, compact pigweed, corn, sugarcane, and soybean leaves had the lowest reflectances (45.1 to 46.0 percent), and dorsiventral bean, orange, and pepper leaves with very porous mesophyll had the highest reflectances (51.0 to 56.2 percent).

At the 1,000-nm. wavelength, the mean transmittance of all crop leaves was 47.9 ± 3.7 percent. All crops fell within this range except orange (38.9 percent) and bean (42.0 percent) and soybean, pigweed, and onion (52.2 to 54.0 percent).

The mean absorptance of all crop leaves at the 1,000-nm. wavelength was 4.0 ± 1.7 percent. Soybean and bean leaves (1.8 percent) and sugarcane, tomato, and onion leaves (6.7 to 7.5 percent) fell outside the 4.0 ± 1.7 percent range.

Correlation coefficients equal to or larger than ± 0.775 are considered that accounted for at least 60 percent of the variation ($0.775^2 \times 100$) between comparisons. Negative coefficients exceeding −0.775 were obtained for correlations between light reflectance and percent leaf-water content for sugarcane at 1,450-, 1,650-, and 2,200-nm.; for corn at 550- and 1,450-nm.; for pigweed at 1,450-nm.; and for tomato at 1,450- and 2,200-nm. wavelengths. Soybean had positive coefficients exceeding 0.775 for the correlation between reflectance and leaf thickness at the 550-, 800-, and 1,000-nm. wavelengths, and a negative coefficient that exceeded −0.775 for the correlation between transmittance and leaf thickness at the 1,000-nm. wavelength. Soybean leaves also had large negative coefficients for the correlation between reflectance and leaf thickness at the 1,450-, 1,950-, and 2,200-nm. wavelengths, and for the correlation between transmittance and leaf thickness at the 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths. Peach, pigweed, tomato, bean, and onion crops also had high negative coefficients for the correlation between transmittance and leaf thickness at two or more of the 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths. High positive coefficients were obtained for the correlation between leaf thickness and percent light absorptance for the soybean, peach, pigweed, bean, and onion crops at three or more of the 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths.

The grams of water per cubic centimeter of leaf tissue were calculated for each crop leaf used, except wheat. There was no correlation between reflectance and grams of water per cubic centimeter of leaf tissue. For transmittance, coefficients exceeded −0.775 only for okra leaves at 1,000-, 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths. The correlation between absorptance and grams of water per cubic centimeter of leaf tissue gave high positive coefficients for okra leaves at 1,450, 1,650, and 2,200 nm.

Experimental values of leaf reflectance and transmittance for the 20 crops have been transformed into effective optical constants. Such optical constants are useful in the prediction of reflectance phenomena associated with leaves either stacked in a spectrophotometer or arranged naturally in a plant canopy. The index of refraction n is plotted against wavelength to obtain dispersion curves. The values for the absorption coefficient k that are tabulated for the various crops are equivalent to values determined previously for leaves from agricultural crops.

The dispersion curves of most of the crop leaves were remarkably similar in shape and in relatively close confidence bands. Onion, pigweed, and lettuce were exceptions, but only one-half of the tubular onion leaves (split longitudinally) was used; lettuce leaves were immature; and veins of pigweed leaves are surrounded by large, cubical, parenchymatous cells.

Sixteen of the 20 crops were analyzed to determine the thickness of water necessary to produce the observed leaf absorption and the number of identical compact layers into which the equivalent water must be subdivided to achieve the observed partition of light between reflectance and transmittance. Sugarcane, corn, sorghum, and wheat leaves were not included because laboratory determinations of thickness and water content were not made on entire leaves. There was no statistically significant difference between observed and computed values for leaf water for 10 of the crops. Pumpkin, avocado, okra, tomato, cantaloup, and lettuce showed differences, but they were not highly significant.

The limiting value of reflectance from leaves piled sufficiently deep is termed *infinite reflectance*. This parameter is a function of the calculated thickness of the identical compact layers of which a leaf is assumed to be composed. Infinite reflectance has been tabulated at 1.65 μ for the 20 crops.

Introduction

To interpret remote-sensing data from aircraft and spacecraft, the reflectance produced by features on the earth's surface must be understood (*33*).[3] The specific problem in agriculture is interpretation of reflectance produced by vegetation, usually superimposed on a soil background. Plant leaves yield most of the signal measured by remote sensors in aircraft and spacecraft. Therefore, they are of prime interest in characterizing vegetation, and their interaction with electromagnetic radiation must be understood.

The purpose of research reported here was to relate the leaf mesophyll structure of 20 important agricultural plant genera to their light spectra and to optical and geometrical parameters. This report is a sequel to a technical monograph by Gausman and others (*15*), which presented research results on the spectral-energy relations of leaves for 11 plant genera characterized by marked differences in leaf-mesophyll arrangements. The research was based on the hypothesis that leaf-mesophyll arrangements influence spectral-energy relations of leaves and plant canopies. Previous research had considered only the relation of light reflectance to leaf surface morphologies (*28*) and to isobilateral leaves (*18*).

Plants studied were corn (*Zea mays* L.), banana (*Musa acuminata* Colla (*M. cavendishii* Lamb.), begonia (*Begonia cu-*

[3] Italic numbers in parentheses refer to Literature Cited, p. 43.

cullata Willd. (*B. semperflorens* Link & Otto), eucalyptus (*Eucalyptus camaldulensis* Dehnh. (*E. rostrata* Schlecht), rose (*Rosa* var. unknown), hyacinth (*Eichhornia crassipes* (Mart.) Solms. sedum (*Sedum spectabile* Boreau), ficus (*Ficus elastica* Roxb. ex Hornem.) oleander (*Nerium oleander* L., Ligustrum (*Ligustrum lucidum* Ait.), and crinum (*Crinum fimbriatulum* Baker).

Differences in leaf mesophylls among the 11 plant genera (15) were compared with: (1) Spectrophotometrically measured reflectance and transmittance and calculated absorptance values of the leaves over the 500- to 2,500-nanometer (nm.)[4] wavelength interval, (2) percent leaf-water contents (oven-dry weight basis), (3) leaf-thickness measurements, and (4) optical and geometrical leaf parameters.

Percent leaf-water contents of the 11 plant genera ranged from 60 percent for isolateral[5] (palisade layers on both sides) eucalyptus to 95 percent for succulent sedum and begonia leaves with storage cells on each side of a central chlorenchyma.

Dorsiventral rose and compact corn leaves (no palisade cells) were thinnest (about 0.15 mm.), and succulent sedum leaves were thickest (about 0.82 mm.).

Spectral data for upper (adaxial) and lower (abaxial) leaf surfaces of all genera for 550-, 800-, 1,000-, 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths were appended. Spectra of upper leaf surfaces of oleander, corn, hyacinth, and eucalyptus were charted. At the 1,000-nm. wavelength, diffuse reflectance was highest for dorsiventral oleander and lowest for compact corn leaves; transmittance was lowest for oleander and highest for corn leaves; and absorptance for corn and oleander leaves was approximately 3 and 9 percent, respectively. The compact corn leaf with low light reflectance and high transmittance has fewer intercellular air spaces than the dorsiventral oleander leaf.

Because the interaction of plant genera with wavelength was small, mean spectral measurements of 550-, 800-, 1,000-, 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths were compared. Lower leaf surfaces of dorsiventral leaves had higher reflectance values than upper leaf surfaces, indicating that the spongy parenchyma contribute more to light scattering than the palisade parenchyma

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[4] Both nanometer (nm.) and micron (μ) are used here to denote spectral wavelengths. A nanometer is one thousandth of a micron, and a micron is one thousandth of a millimeter.

[5] Botanical terms are defined in the Glossary of Terms, p. 58.

of the leaf mesophyll. This was substantiated by equal reflectance values of upper and lower surfaces of compact corn leaves.

Thick leaves of oleander, crinum, ficus, sedum, and ligustrum had the lowest percent transmittance. Mean spectrophotometrically measured transmittance values for the above wavelengths were lower when light was passed from the top through the leaves than when light was passed through from the bottom. The difference in transmittance was caused by greater light diffusion by upper leaf surfaces, since the spectrophotometer used irradiates the specimen with direct light.

Diffuse reflectance data were made absolute by correcting for decay of the magnesium-oxide standard on the spectrophotometer, and absorptance was calculated as: 100 − [percent reflectance + percent transmittance]. When data for wavelengths were averaged, highest absorptance values of 60.6, 58.2, 59.1, and 58.3 percent were obtained for the thick, dorsiventral ficus, crinum, ligustrum, and oleander leaves, respectively; and lowest values of 40.4 and 39.0 percent were obtained for the thin, compact corn and thin, dorsiventral rose leaves, respectively.

Intensive study was given to the 550- and 1,000-nm. wavelengths, representing the visible (400 to 750 nm.) and near-infrared (750 to 1,450 nm.) regions, respectively. At the 550-nm. wavelengths, reflectance was greater from the lower surface than from the upper surface of dorsiventral leaves, indicating that the chloroplasts in the palisade cells absorbed light. Lower and upper surface reflectances were the same for the compact corn leaves. Considering upper leaf surfaces only, thick, succulent sedum and thick ficus leaves had the highest and lowest reflectance values, of 20 and 8 percent, respectively.

Percent transmittance was lowest for ficus and highest for succulent begonia leaves. Compact leaves of corn and succulent leaves of sedum and begonia, with essentially a continuous mesophyll arrangement, had the lowest light absorptance, of approximately 70 percent. Thick dorsiventral leaves of ficus, oleander, and ligustrum, with multiseriate epidermal layers or multipalisade layers, had the highest light absorptance of 80 to 90 percent.

At the 1,000-nm. wavelength, reflectance values from upper and lower leaf surface measurements were essentially alike. Compact corn leaves had the lowest reflectance (43 percent), and succulent sedum and dorsiventral ficus, oleander, ligustrum, and crinum leaves had the highest reflectance (53 percent). The 35.0

percent transmittance of oleander leaves was lowest, and 54.5 percent for corn was highest. The thin corn and rose leaves had the lowest absorptance values (2 to 3 percent), and the thick leaves of ligustrum, ficus, crinum, sedum, and oleander had the highest values (8 to 11 percent).

Correlation coefficients were considered that accounted for at least 60 percent of the variation (r^2 x 100) between leaf thickness and reflectance; leaf thickness and absorptance; leaf-water content and reflectance; and leaf-water content and absorptance. Oleander, eucalyptus, and hyacinth leaves gave the highest coefficients among the plant genera studied. In general, coefficients were negative between water content and reflectance and between thickness and reflectance measurements; and, with the main exception of eucalyptus, coefficients were positive between leaf-water content and absorptance and between thickness and absorptance calculations at 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths.

Experimental values of leaf reflectance and transmittance for the 11 genera were transformed into effective optical constants. Such optical constants are useful in the prediction of reflectance phenomena associated with leaves either stacked in a spectrophotometer or arranged naturally in a plant canopy. The index of refraction n was plotted against wavelength to obtain dispersion curves. The absorption coefficient k was shown to be equivalent to values determined previously for leaves from agricultural crops.

Each of the 11 genera has been analyzed to obtain geometrical parameters that specify the amount of water and air in the leaf. The water parameter is the thickness of liquid water necessary to produce the observed leaf absorption. Observed and computed values of leaf-water thickness were obtained. Agreement was good except for ligustrum, crinum, and sedum. The air parameter is the number of identical compact layers into which the equivalent water must be subdivided to achieve the observed partition of light between reflectance and transmittance.

A third parameter, infinite reflectance, is observed when leaves are piled sufficiently deep. Infinite reflectance was tabulated at 1.65 μ for all 11 genera. Infinite reflectance was shown to be a function of the calculated thickness of the identical compact layers of which a leaf is assumed to be composed.

The literature dealing with the interaction of light with plant leaves and leaf mesophyll structure is reviewed in the technical monograph by Gausman and others (*15*) and is not repeated here. Attention is directed, however, to the research of Aboukhaled [6] who related the optical properties of leaves to their energy-balance, photosynthesis, and water-use efficiency.

Materials and Methods

Twenty plant genera were selected that are presently economically important or have the potential of becoming valuable in the Texas Lower Rio Grande Valley. Pigweed was considered here as a crop rather than a weed, because it is used by some farmers as a plow-under or green-manure crop. The leaves of the selected genera varied in mesophyll arrangement, thickness, water content, and other structural differences such as palisade-layer arrangement. Leaf characteristics of the 20 crops and the families they represent are indicated in table 1, and typical photomicrographs of leaf transections are depicted in figure 1.

All plants were field grown in the summer of 1970, except that lettuce and onions were purchased fresh at a local market, soybeans and beans were grown in a greenhouse, and wheat was grown during the 1969 season.

Ten mature and healthy-appearing leaves were sampled from each of the 20 plant genera. Immediately after excision, leaves were wrapped in Saran or Glad-Wrap [7] to minimize dehydration. Leaves were wiped with a slightly dampened cloth to remove surface contaminants before spectrophotometric measurements. The tubular onion leaf was split longitudinally, and only one-half was measured.

A Beckman Model DK–2A spectrophotometer equipped with a reflectance attachment was used to measure spectral diffuse

[6] Aboukhaled, A. Optical properties of leaves in relation to their energy-balance, photosynthesis, and water use efficiency. (Ph.D. thesis.) University of Calif. Library, Davis. 139 pp. 1966.

[7] Trade names are used in this publication solely for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or an endorsement by the Department over other products not mentioned.

FIGURE 1.—Photomicrographs of leaf transections of 20 plant genera differing in leaf thickness, mesophyll arrangement, and other gross structural characteristics. *A*, avocado; *B*, bean; *C*, cantaloup; *D*, corn; *E*, cotton; *F*, lettuce; *G*, okra; *H*, onion; *I*, orange; *J*, peach; *K*, pepper; *L*, pigweed; *M*, pumpkin; *N*, sorghum; *O*, soybean; *P*, sugarcane; *Q*, sunflower; *R*, tomato; *S*, watermelon; and *T*, wheat.

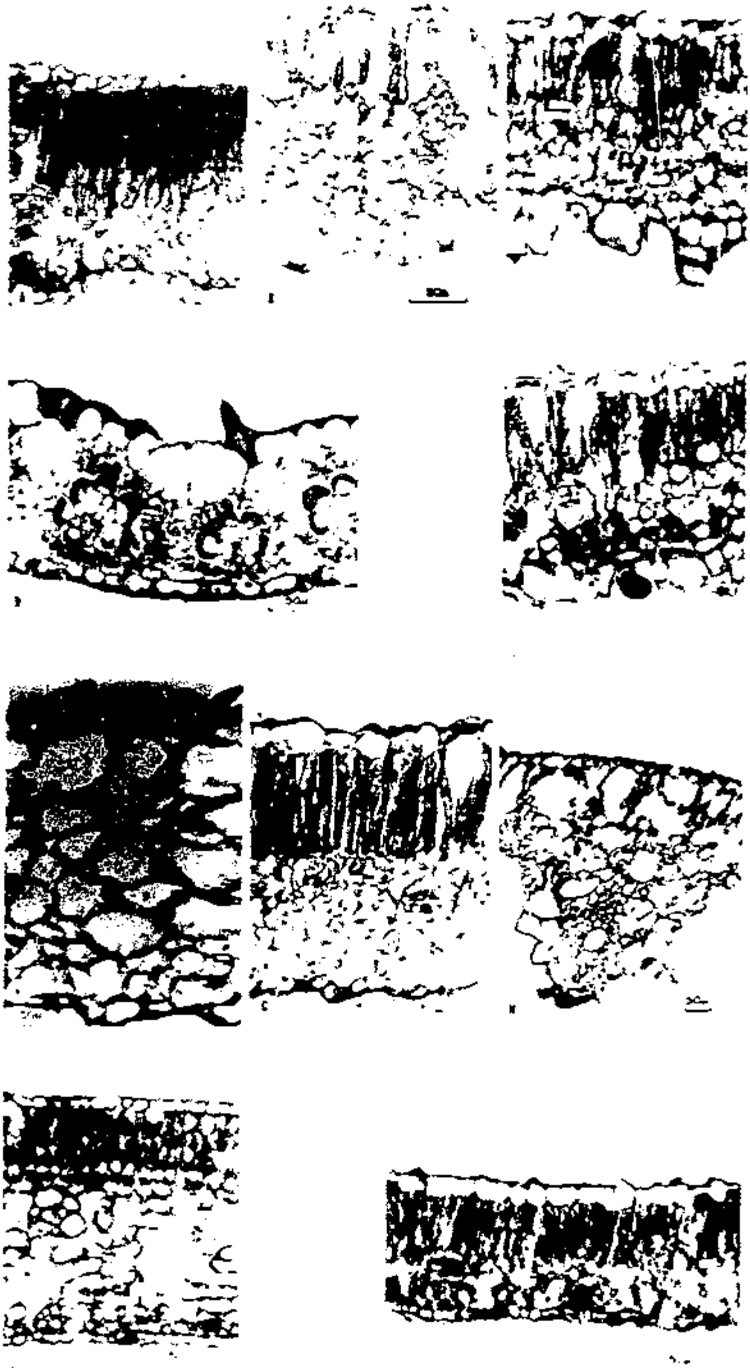

FIGURE 1.—Continued.

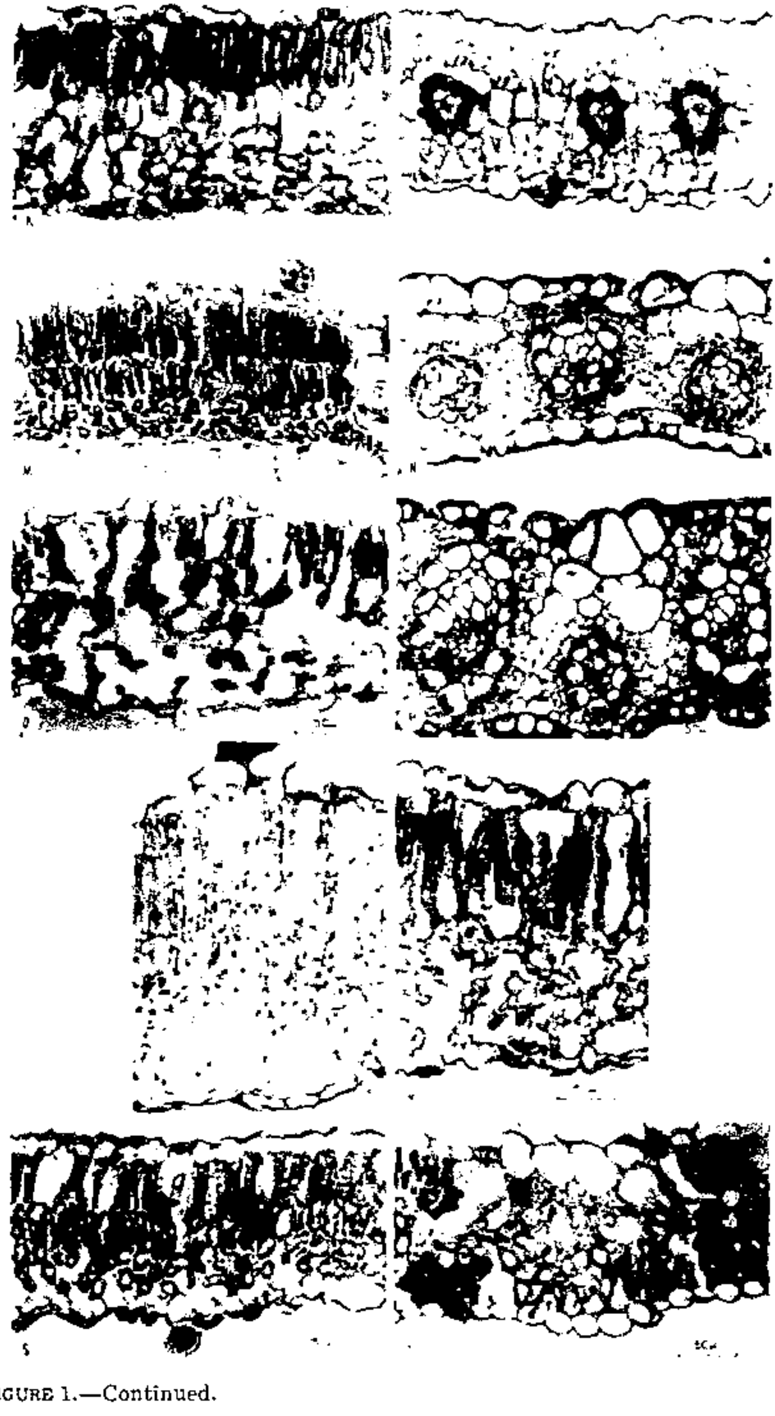

FIGURE 1.—Continued.

reflectance and transmittance on adaxial (upper) surfaces of single leaves over the 500- to 2,500-nm. wavelength interval. Data have been corrected for decay of the magnesium-oxide standard (*27*) to give absolute radiometric data. Absorptance was calculated from the absolute values as: Percent absorptance = 100 − (percent reflectance + percent transmittance).

Measurements of leaf thickness and diffuse reflectance and transmittance and fixation of tissue were completed within 6 hours after leaves were harvested or obtained for each genus.

Leaf thickness was measured with a linear-displacement transducer and digital voltmeter (*17*). Leaf area was determined with a planimeter, except that area per leaf of corn, sorghum, and sugarcane was calculated by the method of Slickter, Wearden, and Pauli (*29*); and area per leaf of cotton was calculated by Johnson's method (*20*). Percent leaf-water content was determined on an oven-dry weight basis by drying at 68° C. for 72 hours and cooling in a desiccator before final weighing. Leaf thickness and water-content determinations were not made on wheat leaves.

Tissue pieces, taken near the center of leaves approximately one-half inch on either side of the midrib, were fixed in formalin-acetic acid-alcohol, dehydrated with a tertiary butanol series, embedded in paraffin, stained with either the safranin-fast green or the safranin-fast green-orange G combinations (*19*), and transversally microtomed at 12- or 14-μ thickness. The relatively thick transverse sections were used to accentuate intercellular spaces, and thus enhance differences in mesophyll arrangements among the crops. Photomicrographs were obtained with a Zeiss Standard Universal Photomicroscope.

Spectrophotometrically measured reflectance and transmittance, and calculated absorptance of seven wavelengths (550, 800, 1,000, 1,450, 1,650, 1,950, and 2,200 nm.) were analyzed for variance (*30*). Duncan's Multiple Range Test (*7*) was used to test differences among means of the seven wavelengths at the 5-percent probability level. Standard deviation was calculated to compare the leaf reflectance, transmittance, and absorptance of the crops at the 550- and 1,000-nm. wavelengths. Coefficients were calculated to evaluate the correlation of leaf thickness with leaf-water content. Coefficients were also obtained for correlations of reflectance, transmittance, and absorptance with grams of water per cubic centimeter of leaf tissue, leaf-water content on an oven-dry weight basis, and leaf thickness. Correlation coefficients of ± 0.775 were chosen as levels of significance because they ac-

TABLE 1.—*Common, scientific, and family names; leaf mesophyll arrangements; and structural characteristics of plant leaves used in this study*

Common name [1]	Scientific name [2]	Family name	Mesophyll arrangement [3]	Additional structural characteristics [4]
Avocado	*Persea americana* Mill.	*Lauraceae*	Dorsiventral	Thick cuticle, multiple palisade layers, long and narrow palisade cells.
Bean	*Phaseolus vulgaris* L.	*Leguminosae*	Dorsiventral	Very porous mesophyll.
Cantaloup	*Cucumis melo* L. var. *cantalupensis* Naud.	*Cucurbitaceae*	Dorsiventral	Multiple palisade layers, hairs lower epidermis.
Corn	*Zea mays* L.	*Gramineae*	Compact	Bulliform cells, hairs upper epidermis.
Cotton	*Gossypium hirsutum* L.	*Malvaceae*	Dorsiventral	Glandular hairs, nectaries, lysigenous glands.
Lettuce	*Lactuca sativa* L.	*Compositae*	Compact	Large cells, porous mesophyll.
Okra	*Hibiscus esculentus* L.	*Malvaceae*	Dorsiventral	Well-differentiated, porous mesophyll.
Onion	*Allium cepa* L.	*Amaryllidaceae*	Dorsiventral	Tubular leaves.
Orange	*Citrus sinensis* (L.) Osbeck	*Rutaceae*	Dorsiventral	Thick cuticle with wax layers, multiple palisade layers, lysigenous cavities.
Peach	*Prunus persica* (L.) Batsch.	*Rosaceae*	Dorsiventral	Multiple palisade layers, porous mesophyll.
Pepper	*Capsicum annuum* L. and other spp.	*Solanaceae*	Dorsiventral	Druse crystals.
Pigweed	*Amaranthus retroflexus* L.	*Amaranthaceae*	Compact	Druse crystals, veins surrounded by large, cubical, parenchymatous cells.

Pumpkin	*Cucurbita pepo* L.	*Cucurbitaceae*	Dorsiventral	Multiple palisade layers, hairs upper and lower epidermis.
Sorghum	*Sorghum bicolor* (L.) Moench.	*Gramineae*	Compact	Bulliform cells.
Soybean	*Glycine max* (L.) Merr.	*Leguminosae*	Dorsiventral	Porous mesophyll.
Sugarcane	*Saccharum officinarum* L.	*Gramineae*	Compact	Bulliform cells.
Sunflower	*Helianthus annuus* L.	*Compositae*	Isolateral	Hairs upper and lower epidermis.
Tomato	*Lycopersicon esculentum* Mill.	*Solanaceae*	Dorsiventral	Hairs upper and lower epidermis, glandular hairs lower surface.
Watermelon	*Citrullus lanatus* (Thunb.) Mansf.	*Cucurbitaceae*	Dorsiventral	Multiple palisade layers, glandular hairs lower surface.
Wheat	*Triticum aestivum* L.	*Gramineae*	Compact	Bulliform cells.

[1] Generic names used as common names are not italicized or capitalized in the text.

[2] Names are those formerly used by New Crops Research Branch, ARS, USDA, Beltsville.

[3] Arbitrary definitions of mesophyll arrangements used herein are: Dorsiventral, a usually porous (many intercellular air spaces) mesophyll with palisade parenchyma cells in its upper part and spongy parenchyma cells in its lower part; compact, mesophyll with little intercellular air space and no differentiation into palisade and spongy parenchyma cells; isolateral, a porous mesophyll that tends to have long narrow cells throughout.

[4] Definitions are given in the Glossary of Terms, p. 58. References used were Esau (*8*), Fahn (*9*), Hayward (*16*) and Metcalfe and Chalk (*23*).

count for 60 percent of the variation (r^2 x 100) between two series of variates. This is often referred to as the biological level of significance.

Results and Discussion

Mature leaves were used because leaf age affects spectral-energy relations, leaf-water contents, and leaf thicknesses (*13*).

The influence of leaf maturation on reflectance and transmittance is associated with compactness of internal cellular structure. Differences in cellular compactness of cotton leaves, sampled from fourth or fifth nodes down from plant apexes, affected reflectance of near-infrared light over the 750- to 1,350-nm. wavelength intervals (*12, 14*). Reflectance of older leaves was increased because of an increase in intercellular air spaces. Scattering of light within leaves occurs most frequently at interfaces between cell walls (hydrated cellulose) and air cavities, which have refractive indexes of 1.4 and 1.0, respectively (*32, 34*).

Very immature cells in young leaves are primarily protoplasmic, with little vacuolate cell-sap storage (*8, 9, 22*). During cell growth (extension), cell water-filled vacuoles develop, which usually coalesce to form a central sap cavity, and the protoplasm covers the cell wall in a thin layer. Hydrated leaves, compared with dehydrated leaves, reflected less and absorbed more light over the 500- to 2,500-nm. wavelength interval (*4*).

To facilitate interpretation, the 500- to 2,500-nm. wavelength interval has been subdivided into three intervals (modified after Thomas, Wiegand, and Myers (*31*): (1) the visible-light absorptance region 500 to 750 nm., dominated by pigments (primarily chlorophylls a and b, carotene, and xanthophylls); (2) the near-infrared region 750 to 1,350 nm., a region of high reflectance and low absorptance considerably affected by internal leaf structure; and (3) the 1,350- to 2,500-nm. wavelength interval, a region influenced to some degree by leaf structure, but greatly affected by the amount of water in tissue—strong water-absorption bands occur at 1,450 and 1,950 nm. Data for reflectance, transmittance, and absorptance (representing means of 10 replications of each of 20 crops) for the 41 wavelengths are given in tables 12, 13, and 14 (Appendix). Reflectance, transmittance, and absorptance spectra for the 20 crops are charted in figure 2.

Leaf water and thickness

Figure 3 depicts the leaf-water contents of 19 crops (wheat not included) on a dry-weight basis. Thick, succulent lettuce

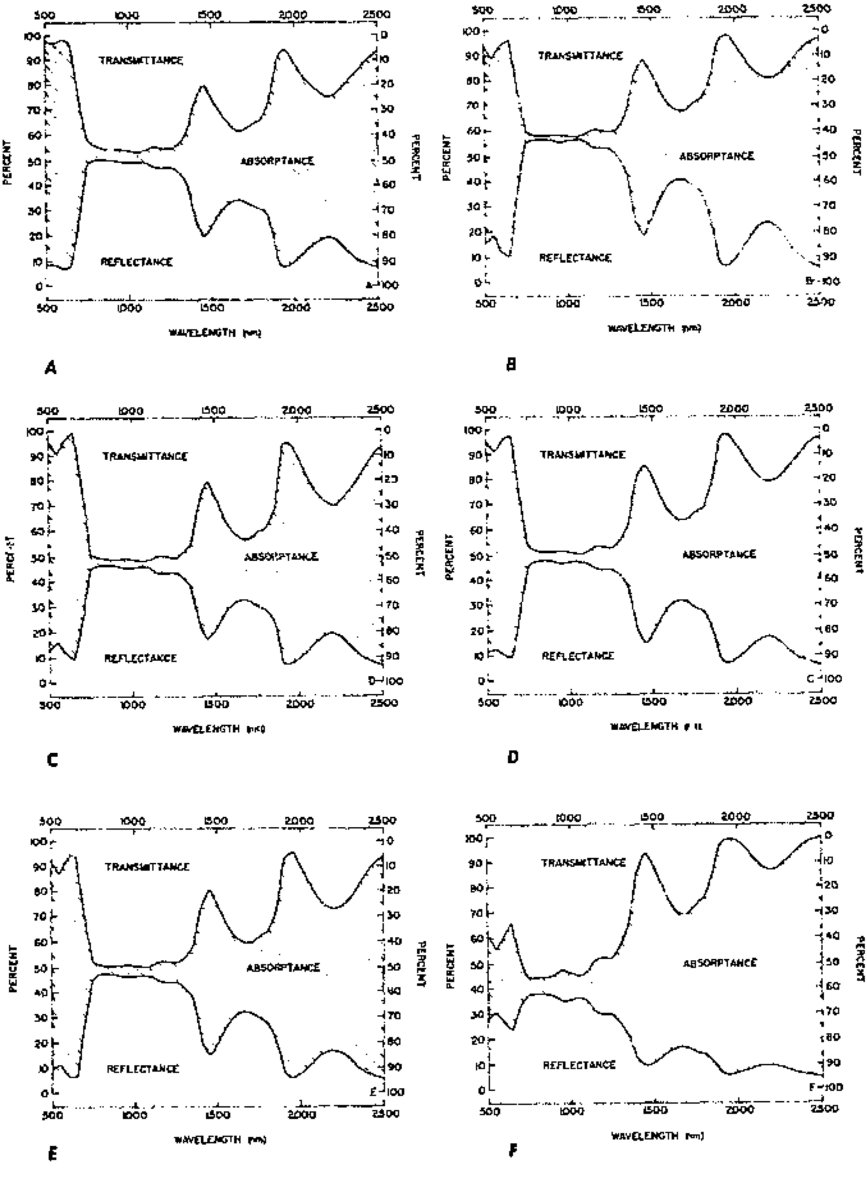

FIGURE 2.—Light reflectance, transmittance, and absorptance spectra of the leaves of 20 crops for the 500- to 2,500-nm. wavelength interval. *A*, avocado; *B*, bean; *C*, cantaloup; *D*, corn; *E*, cotton; *F*, lettuce; *G*, okra; *H*, onion; *I*, orange; *J*, peach; *K*, pepper; *L*, pigweed; *M*, pumpkin; *N*, sorghum; *O*, soybean; *P*, sugarcane; *Q*, sunflower; *R*, tomato; *S*, watermelon; and *T*, wheat.

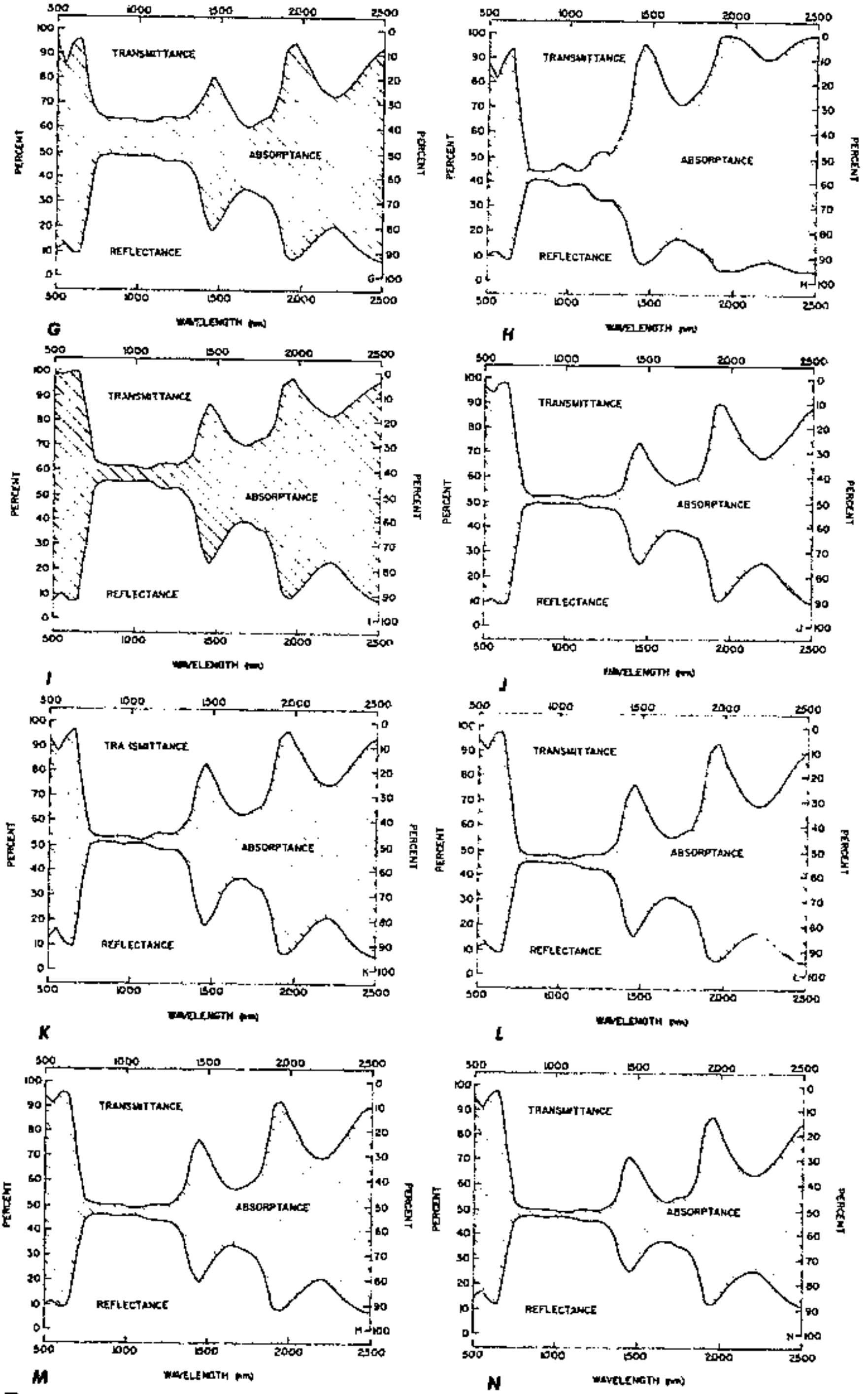

FIGURE 2.—Continued.

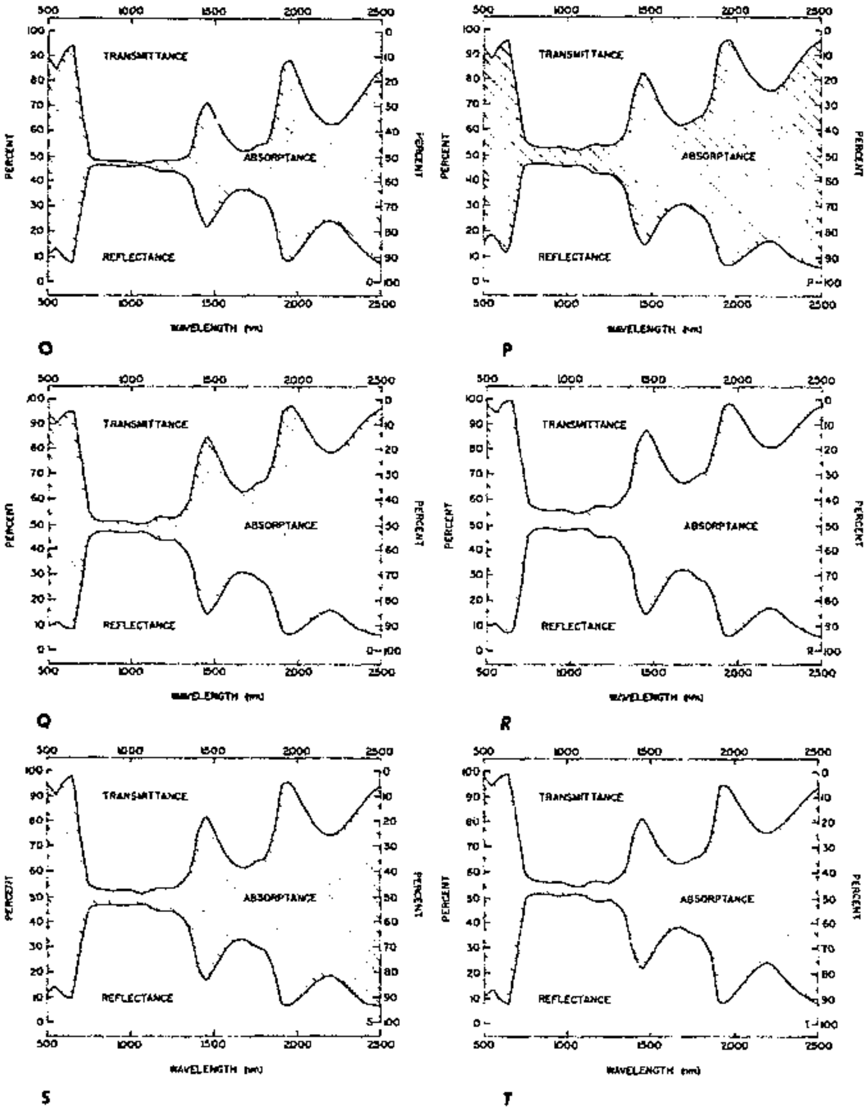

FIGURE 2.—Continued.

leaves had significantly the highest water content of 97.0 percent. The significantly lowest water contents were in avocado, orange, peach, and sugarcane leaves (60.6 to 72.4 percent), which as a group were statistically alike (Duncan's Test). Okra, soybean, pigweed, cotton, and watermelon leaves had essentially the same water contents, 80.6 to 82.4 percent. Four other groups with similar water contents within each group were corn and sorghum; sunflower and pumpkin; pepper and cantaloup; and bean and onion. In some leaves, results show no apparent association of leaf-mesophyll arrangement with leaf-water content. For example, dorsiventral leaves had both high (bean and onion) and low (avocado and orange) leaf-water contents. However, compact corn, sorghum, and sugarcane leaves within the family *Gramineae* and dorsiventral cotton and okra leaves within the family *Malvaceae* had quite similar water contents.

Figure 4 portrays leaf thicknesses of 19 crops (wheat not included). Sunflower, cantaloup, lettuce, and onion leaves were thickest (0.407 to 0.978 mm.), and soybean, peach, pumpkin, and

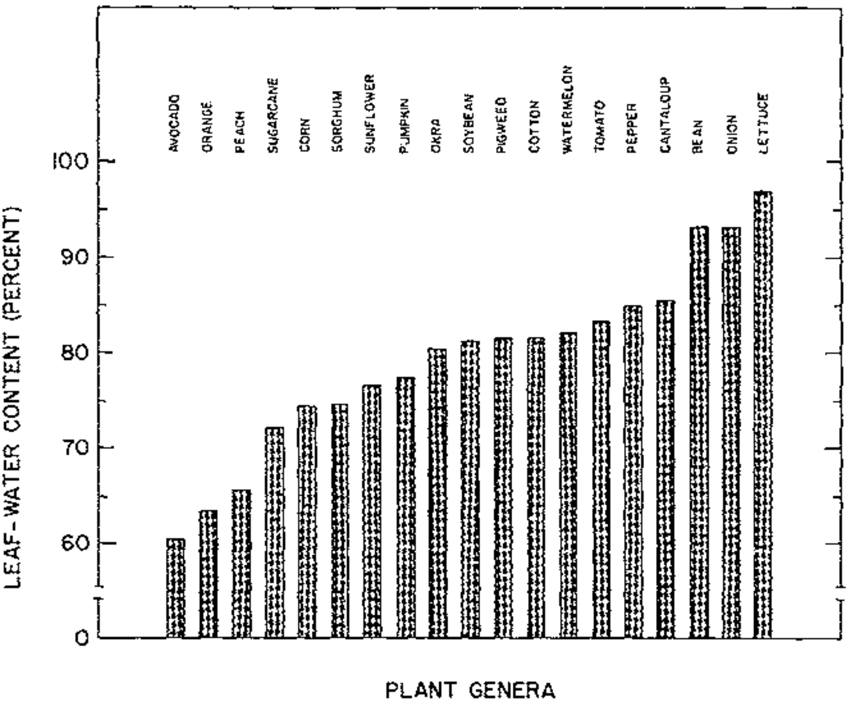

FIGURE 3.—Percent leaf-water content on an oven-dry weight basis of 19 crops (wheat excluded), arranged in ascending order of water content.

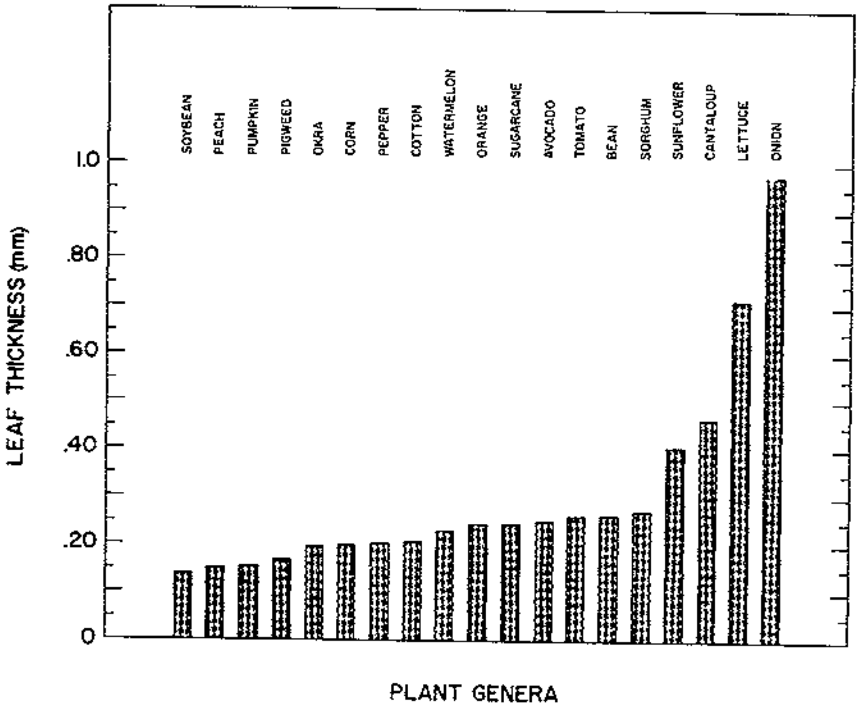

FIGURE 4.—Leaf thickness of 19 crops (wheat excluded), arranged in ascending order of thickness.

pigweed leaves were thinnest (0.140 to 0.170 mm.), compared with the other crop leaves. Other groups with statistically alike leaf thicknesses were: Pigweed, okra, corn, pepper (0.170 to 0.203 mm.); okra, corn, pepper, cotton, watermelon (0.198 to 0.232 mm.); watermelon, orange, sugarcane, avocado, tomato, and bean (0.232 to 0.263 mm.); and orange, sugarcane, avocado, tomato, bean, and sorghum (0.245 to 0.274 mm.). Within the families *Malvaceae* and *Gramineae,* cotton and okra, and sugarcane and sorghum, respectively, were alike in leaf thickness.

Correlations of leaf thickness with water content of 19 crops were made (wheat not included). Highest coefficients obtained were 0.58, 0.58, 0.57, and 0.56 for avocado, orange, tomato, and sorghum leaves, respectively, accounting for only 31 to 34 percent (r^2 x 100) of the variation between leaf thicknesses and leaf-water contents. Remaining coefficients, with respective crops, were: Peach, −0.51; lettuce, 0.50; bean, 0.50; cotton, 0.48; watermelon, 0.45; corn, 0.43; soybean, 0.42; pepper, 0.41; pigweed, 0.40; sugarcane, 0.36; sunflower, 0.30; cantaloup, 0.29;

pumpkin, 0.26; okra, 0.05; and onion, 0.03. Thus leaf thickness and water content of leaves are poorly correlated. There is no reason, however, why leaf thickness should be correlated with water content unless the ratio of water-storage cells to non-water-storage cells differs. This could feasibly be true of succulent leaves.

Spectrophotometric measurements for seven selected wavelengths

To reduce the enormous amount of spectrophotometrically generated data and facilitate interpretation, seven wavelengths were selected from the 41 wavelengths measured at 50-nm. increments over the 500- to 2,500-nm. wavelength interval. Wavelengths selected were 550, 800, 1,000, 1,450, 1,650, 1,950, and 2,200 nm.; representing, respectively, the visible region, the beginning of the near-infrared plateau, a wavelength on the near-infrared plateau, the 1,450-nm. water-absorption band, the 1,650-nm. peak following the 1,450-nm. water-absorption band, the 1,950-nm. water-absorption band, and the 2,200-nm. peak following the 1,950-nm. water-absorption band.

The means of the seven wavelengths will be briefly discussed, followed by an introduction to leaf spectra over the 500- to 2,500-nm. wavelength interval, using the complementary 550- and 1,000-nm. wavelength data. The 550-nm. wavelength data will be used to assess relative differences in chlorophyll concentrations of the crop leaves, and the 1,000-nm. wavelength data will be used to evaluate the influence of leaf mesophyll arrangements on light reflectance.

Table 2 presents the means of the selected seven wavelengths for the reflectance, transmittance, and absorptance by leaves of the 20 crops. Considering reflectance, onion had the lowest (18.1) and bean leaves the highest (31.6) percent reflectance. Groups that had like but intermediate levels of reflectance were sunflower, pigweed, and cotton; pigweed, cotton, and tomato; cotton, tomato, sugarcane, and cantaloup.

Statistically, orange leaves had the lowest transmittance (20.4), and soybean leaves had the highest (34.9) percent. Three groups, each alike in transmittance, were wheat, cantaloup, sunflower, and avocado (25.6 to 26.3); pepper, sugarcane, watermelon, and okra (27.1 to 27.9); and corn, peach, and pumpkin (30.0 to 30.6 percent).

Among the 20 crops, onion leaves had the significantly highest absorptance of 57.4, and sorghum and soybean leaves as a group had the lowest absorptance (36.7 to 36.9) percent. Other groups

TABLE 2.—*Average percent reflectance, transmittance, and absorptance of light of seven wavelengths (550, 800, 1,000, 1,450, 1,650, 1,950, and 2,200 nm.) by 10 leaves of each of 20 crops*

Crop	Reflectance[1]	Crop	Transmittance[1]	Crop	Absorptance[1]
	Percent		*Percent*		*Percent*
Onion	18.1a	Orange	20.4a	Sorghum	36.7a
Lettuce	20.6 b	Bean	22.9 b	Soybean	36.9a
Sunflower	24.8 c	Tomato	23.0 b	Peach	39.7 b
Pigweed	24.9 cd	Onion	24.5 c	Pumpkin	42.9 c
Cotton	25.3 cde	Wheat	25.6 d	Corn	43.6 cd
Tomato	25.4 de	Cantaloup	25.7 d	Pigweed	43.7 cd
Sugarcane	25.5 e	Sunflower	26.1 d	Pepper	44.1 de
Cantaloup	25.5 e	Avocado	26.3 de	Wheat	44.5 de
Watermelon	26.2 f	Pepper	27.1 ef	Okra	44.8 ef
Corn	26.4 f	Sugarcane	27.3 f	Bean	45.5 fg
Pumpkin	26.5 f	Watermelon	27.4 f	Cotton	45.6 fg
Avocado	27.0 g	Okra	27.9 f	Watermelon	46.4 gh
Okra	27.3 g	Cotton	29.1 g	Avocado	46.6 h
Soybean	28.2 h	Lettuce	29.2 g	Sugarcane	47.1 h
Pepper	28.9 i	Corn	30.0 h	Orange	48.8 i
Peach	29.8 j	Peach	30.5 h	Cantaloup	48.8 i
Wheat	29.9 j	Pumpkin	30.6 h	Sunflower	49.2 i
Sorghum	30.2 j	Pigweed	31.4 i	Lettuce	50.2 j
Orange	30.8 k	Sorghum	33.1 j	Tomato	51.6 k
Bean	31.6 l	Soybean	34.9 k	Onion	57.4 l

[1] Values within columns followed by the same letter do not differ significantly at the 5-percent level, using Duncan's Multiple Range Test.

of crops that had like absorptances were: Pumpkin, corn, and pigweed; corn, pigweed, pepper, and wheat; pepper, wheat, and okra; okra, bean, and cotton; bean, cotton, and watermelon; and watermelon, avocado, and sugarcane.

Leaf spectra of four selected crops

Reflectance and transmittance spectra (500- to 2500-nm.) of four selected crops (bean, avocado, sorghum, pigweed) are illustrated and compared in figures 5 and 6.

Average reflectances at the 500-nm. wavelength were 18.5, 12.4, 17.2, and 8.9 percent (table 3) for bean, pigweed, sorghum, and avocado leaves, respectively. High reflectances indicate low concentrations of chlorophylls, and conversely, low reflectances indicate high concentrations.

At the 1,000-nm. wavelength, representing the 750- to 1,350-nm. near-infrared wavelength interval, reflectances were 56.2, 49.7, 45.1, and 47.0 percent (table 4) for bean, avocado, pigweed, and sorghum leaves, respectively. The dorsiventral bean and

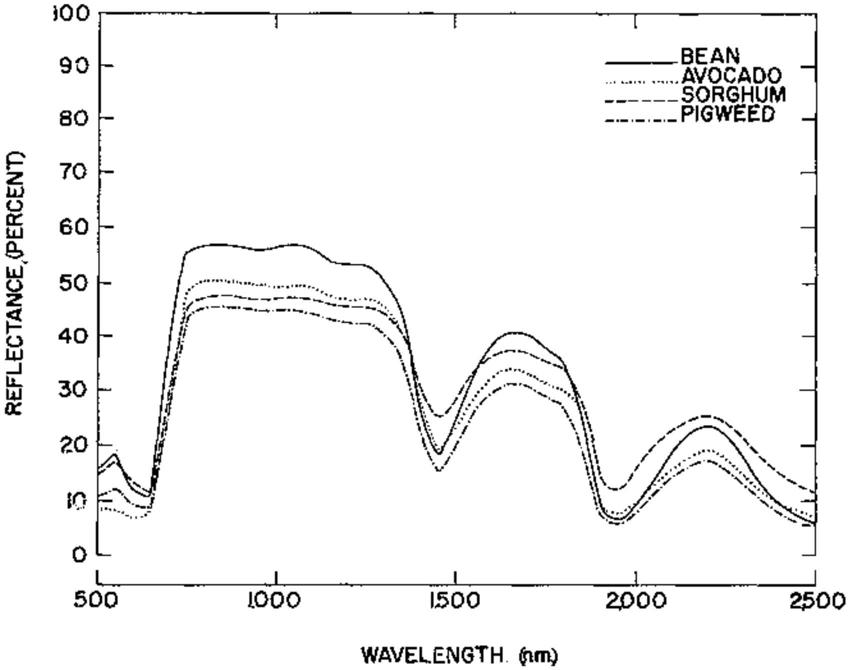

FIGURE 5.—Reflectance spectra of leaves of four crops. Pigweed and sorghum leaves have compact mesophylls; bean and avocado leaves have dorsiventral mesophylls.

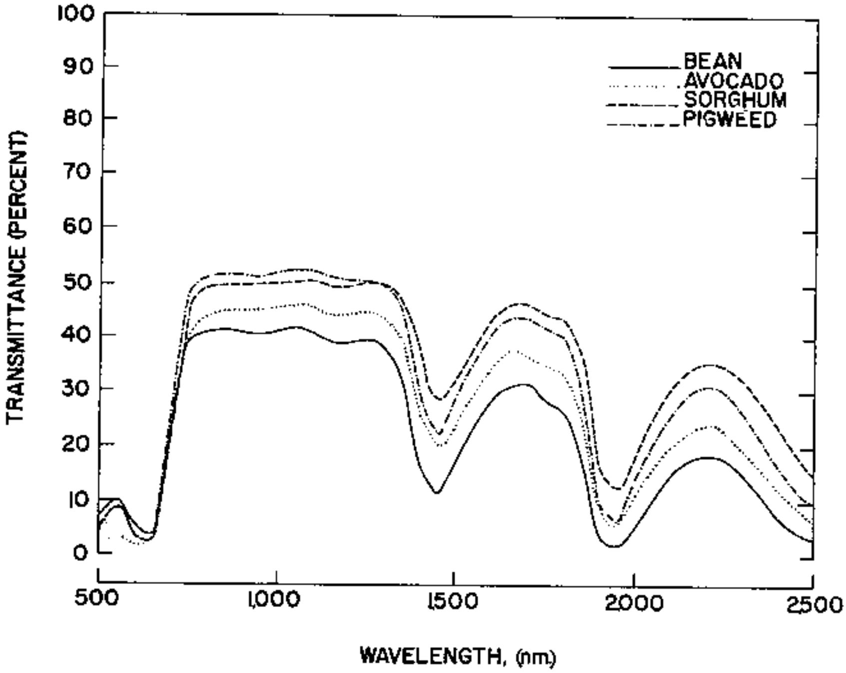

FIGURE 6.—Transmittance spectra of leaves of four crops. Pigweed and sorghum leaves have compact mesophylls; bean and avocado leaves have dorsiventral mesophylls.

avocado leaves with porous mesophylls had higher reflectances than the relatively compact pigweed and sorghum leaves. This aspect will be discussed later.

Transmittance curves were similar in shape to the reflectance curves (fig. 5 and 6). At the 550-nm. wavelength transmittances were 10.9, 9.5, 9.0, and 4.1 percent for bean, pigweed, sorghum, and avocado leaves, respectively. At the 1,000-nm. wavelength, transmittances were 42.0, 46.1, 52.4, and 50.3 percent for bean, avocado, pigweed, and sorghum leaves, respectively.

Calculated absorptances at the 550-nm. wavelength were 70.6, 78.2, 73.8, and 87.0 percent (table 3) for bean, pigweed, sorghum, and avocado leaves, respectively. In the near-infrared (1,000-nm.) region, absorptances were 1.8, 2.5, 2.7, and 4.2 percent for bean, pigweed, sorghum, and avocado leaves, respectively.

Spectrophotometric measurements at the 550-nm. wavelength

Intensive study was given to the 550- and 1,000-nm. wavelength, representing the visible (400 to 750 nm.) and near-

TABLE 3.—*Reflectance, transmittance, and absorptance of light at the 550-nm. wavelength by leaves of 20 crops*

Crop [1]	Reflectance	Crop [1]	Transmittance	Crop [1]	Absorptance
	Percent		*Percent*		*Percent*
Avocado	8.9	Orange	1.9	Lettuce	25.4
Orange	10.2	Avocado	4.1	Sugarcane	69.2
Peach	10.9	Tomato	5.5	Onion	69.7
Tomato	11.0	Wheat	5.8	Bean	70.6
Sunflower	11.0	Peach	6.2	Pepper	70.6
Onion	11.6	Cantaloup	8.7	Soybean	71.3
Pumpkin	11.8	Pumpkin	8.8	Okra	72.2
Cotton	11.8	Sorghum	9.0	Sorghum	73.8
Pigweed	12.4	Sunflower	9.1	Corn	74.0
Cantaloup	12.7	Pigweed	9.5	Cotton	75.1
Okra	12.9	Watermelon	9.6	Watermelon	75.9
Soybean	13.1	Corn	9.8	Pigweed	78.2
Wheat	13.4	Bean	10.9	Cantaloup	78.6
Watermelon	14.4	Sugarcane	12.2	Pumpkin	79.5
Corn	16.2	Pepper	12.6	Sunflower	79.9
Pepper	16.8	Cotton	13.1	Wheat	80.7
Sorghum	17.2	Okra	14.8	Peach	82.9
Bean	18.5	Soybean	15.6	Tomato	83.6
Sugarcane	18.6	Onion	18.8	Avocado	87.0
Lettuce	30.3	Lettuce	44.3	Orange	87.9
Mean [2]	13.3		9.8		76.9
Standard deviation [2]	2.8		4.2		5.8

[1] Crops are arranged in ascending order of their percent reflectance, transmittance, and absorptance.

[2] Lettuce was omitted because leaves were found to be immature.

infrared (750 to 1,350 nm.) spectral regions, respectively. Tables 3 and 4 present light reflectance, transmittance, and absorptance values for the 550- and 1,000-nm. wavelength, respectively.

Mature, healthy leaves have approximately equal reflectance and transmittance. Lettuce leaves became suspect when it was noted that they had 35.3 percent reflectance and 53.7 percent transmittance at the 1,000-nm. wavelength (table 4). Investigation revealed that fourth leaves in from the exterior of the lettuce heads were used. These leaves were not mature. It is characteristic of immature leaves to have a high light transmittance and low reflectance (*13*). Therefore, means and their standard deviations for the data in tables 3 and 4 were calculated omitting the data for lettuce leaves.

The mean reflectance of crop leaves at the 550-nm. wavelength was 13.3 percent ± 2.8 percent (one standard deviation). All crops fell within the 13.3 percent ± 2.8 percent range except avocado and orange (8.9 and 10.2 percent, respectively), and corn, pepper, sorghum, bean, and sugarcane (16.2 to 18.6 percent).

The chlorophyll of green leaves usually absorbs 70 to 90 percent of the light in the blue (about 450 nm.) or red part (about 675 nm.) of the spectrum (*21*). Absorptance is smallest in the wavelength region around 550 nm., where the reflection peak is usually less than 20 percent from upper leaf surfaces. Avocado and orange leaves, with a low reflectance at the 550-nm. wavelength, apparently had a much higher concentration of chlorophyll than corn, pepper, sorghum, bean, and sugarcane leaves,

TABLE 4.—*Reflectance, transmittance, and absorptance of light at the 1,000-nm. wavelength by leaves of 20 crops*

Crop [1]	Reflectance	Crop [1]	Transmittance	Crop [1]	Absorptance
	Percent		*Percent*		*Percent*
Lettuce	35.3	Orange	38.9	Soybean	1.8
Onion	38.5	Bean	42.0	Bean	1.8
Pigweed	45.1	Wheat	44.6	Pepper	2.4
Corn	45.7	Tomato	44.7	Pigweed	2.5
Sugarcane	45.7	Avocado	46.1	Sorghum	2.7
Soybean	46.0	Pepper	46.5	Peach	2.8
Cotton	46.6	Okra	47.3	Corn	3.2
Pumpkin	46.7	Sugarcane	47.6	Pumpkin	3.2
Watermelon	46.8	Watermelon	47.9	Cantaloup	3.9
Sunflower	46.9	Peach	47.9	Cotton	4.0
Sorghum	47.0	Cantaloup	48.8	Okra	4.0
Cantaloup	47.3	Sunflower	49.1	Sunflower	4.1
Tomato	48.3	Cotton	49.4	Wheat	4.2
Okra	48.7	Pumpkin	50.1	Avocado	4.2
Peach	49.3	Sorghum	50.3	Watermelon	5.3
Avocado	49.7	Corn	51.2	Orange	5.5
Pepper	51.0	Soybean	52.2	Sugarcane	6.7
Wheat	51.2	Pigweed	52.4	Tomato	7.0
Orange	55.6	Lettuce	53.7	Onion	7.5
Bean	56.2	Onion	54.0	Lettuce	11.0
Mean [2]	48.0		49.9		4.0
Standard deviation [2]	3.9		3.7		1.7

[1] Crops are arranged in ascending order of their percent reflectance, transmittance, and absorptance.

[2] Lettuce was omitted because leaves were immature.

with a high reflectance at the 550-nm. wavelength. Low pigment content results often in higher reflectance (*5, 25*). J. R. Thomas, Weslaco, Tex. (unpublished data) has shown that crops vary considerably in chlorophyll content. For example, sorghum and cantaloup leaves ranged in chlorophyll concentration from 0.7 to 11.8 and 6.4 to 15.1 mg/g. of plant tissue, respectively. Rabideau, French, and Holt (*26*) found that light-green leaves of cabbage and lettuce had 8 to 28 percent higher reflectance than the average of six darker green species. Thomas also showed a relation between pigment contents of leaves of some crops and their reflectance values.

Among transmittances in table 3, orange, tomato, and avocado (1.9 to 5.5 percent) and okra, soybean, and onion (14.8 to 18.8 percent) fell outside of the 9.8 percent ± 4.2 percent range. *In general, the spectral transmittance curves for all mature and healthy leaves are similar to their spectral reflectance curves over the 500- to 2,500-nm. wavelength interval.*

The differences among the crop leaves in the visible region are most apparent in the figures on the percent absorptance in table 3. The mean absorptance for the crops is 76.9 percent ± 5.8 percent. All crops fell within the 76.9 percent ± 5.8 percent range except sugarcane, onion, bean, and pepper with low absorptances (69.2 to 70.6 percent) and peach, tomato, avocado, and orange with high absorptances (82.9 to 87.9 percent). The leaves with the high absorptances, compared with the leaves with low absorptances, have well-differentiated dorsiventral mesophylls, with many chloroplasts in their dense, palisade parenchyma layers (fig. 1). Aboukhaled[8] made preliminary analyses of the energy balance of single plant leaves from "low and high absorptivity" categories. He concluded that the optical properties of the leaves could be used to partition the total energy absorbed by the leaves into reradiation, convection, and transpiration.

Spectrophotometric measurements at the 1,000-nm. wavelength

The 1,000-nm. wavelength (table 4) can be used to evaluate the influence of leaf-mesophyll arrangement on near-infrared (750 to 1,350 nm.) light reflectance. A leaf with a compact mesophyll has lower light reflectance and concomitantly higher transmittance than a leaf with a porous mesophyll (*12*). In table 4, the mean reflectance of the crop leaves at the 1,000-nm. wavelength was 48.0 percent ± 3.9 percent. The reflectance of

[8] See reference listed in footnote 6, p. 8.

onion (38.5 percent) and orange and bean (55.6 and 56.2 percent, respectively) fell outside of the 48.0 percent ± 3.9 percent range. Only one-half of the tubular onion leaf was used for spectrophotometric measurements. Thus, discounting onion as an unusual leaf, compact pigweed, corn, and sugarcane leaves (fig. 1) had the lowest reflectances (45.1 to 45.7 percent), and dorsiventral leaves with very porous mesophylls such as bean, orange, and pepper had the highest reflectances (51.0 to 56.2 percent). An exception was the high reflectance of wheat leaves (51.2 percent), but examination of its photomicrograph in figure 1 indicates that its mesophyll is more porous than those of corn and sugarcane, even though they are all members of the family *Gramineae* (table 1).

The mean transmittance of all crop leaves (table 4) was 47.9 percent ± 3.7 percent. All crops fell within this range except orange and bean (38.9 and 42.0 percent, respectively) and soybean, pigweed, and onion (52.2 to 54.0 percent). Omitting onion and lettuce leaves for reasons given previously, compact pigweed, sorghum, and pumpkin leaves had high transmittance, and porous dorsiventral leaves had low transmittance. The main exceptions were dorsiventral soybean leaves with relatively high transmittance (52.2 percent) and compact wheat leaves with relatively low reflectance (44.6 percent).

Absorptance values are also given in table 4; the mean of all crop leaves was 4.0 percent ± 1.7 percent. Soybean and bean leaves (1.8 percent) and sugarcane, tomato, and onion leaves (6.7 to 7.5 percent) fell outside the 4.0 percent ± 1.7 percent range. Soybean and bean leaves with the low absorptance of near-infrared light both have extremely porous mesophylls (fig. 1).

Correlations among spectrophotometric measurements and leaf-water content and thickness

Although the literature indicates that thick leaves have higher absorptance than thin leaves (*24, 26*), coefficients for the correlation between absorptance and leaf thickness were low. To make a relative comparison among correlation coefficients, a level of $r = 0.775$ was chosen as the level of significance, because it accounts for 60 percent ($r^2 \times 100$) of the variation for the association between two series of variates. Wheat was not included in calculating correlation coefficients because leaf-water and thickness determinations had not been made.

Coefficients were calculated, using the means of data from 10 leaves of each crop, to test the correlation of leaf thickness, percent water content, and grams of water per cubic centimeter of leaf tissue with reflectance at the 550-, 800-, 1,000, 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths. Negative coefficients that exceeded −0.775 were obtained for the correlation between leaf thickness and reflectance at the 1,450-, 1,650-, and 2,200-nm. wavelengths. There were no high positive correlation coefficients. Correlation coefficients for wavelengths of 800, 1,000, 1,450, 1,650, 1,950, and 2,200 nm. were, respectively: 0.53, −0.42, −0.45, −0.65, −0.53, −0.60, and −0.52 for the relation between leaf-water content and reflectance; 0.30, −0.60, −0.65, −0.76, −0.85, −0.46, and −0.80 for the relation between leaf thickness and reflectance; and 0.07, −0.17, −0.18, −0.31, −0.28, −0.58, and −0.31 for the relation between grams of water per cubic centimeter of plant tissue and reflectance.

The coefficients for correlations of leaf reflectance, transmittance, and absorptance with percent leaf-water content for the 10 leaves of each crop are shown in table 5. Sugarcane, corn,

TABLE 5.—*Coefficients for correlation of reflectance (R), wavelengths with percent leaf-water content of*

Crop [1]	Correlation coefficients [2]								
	550 nm.			800 nm.			1,000 nm.		
	R	T	A	R	T	A	R	T	A
1. Avocado	−0.14	0.52	−0.37	−0.31	0.30	0.17	−0.34	0.21	0.34
2. Orange	−.24	.67	−.31	−.45	.62	−.29	−.49	.61	−.22
3. Peach	−.35	.58	−.15	−.55	.26	.15	−.52	.20	.19
4. Sugarcane	.15	.46	−.41	−.52	.54	−.14	−.56	.48	.00
5. Corn	−<u>.98</u>	.02	.29	−.39	.41	.03	−.39	.38	.13
6. Sorghum	−.52	−.22	.37	−.21	.18	.04	−.28	.06	.22
7. Sunflower	.32	.48	−.50	−.22	−.05	.24	−.26	−.05	.26
8. Pumpkin	.38	.10	−.39	−.18	−.25	.31	−.20	−.25	.35
9. Okra	−.26	.40	−.17	−.24	.11	.15	−.30	.01	.28
10. Soybean	.48	.14	−.52	.07	−.26	.33	.14	−.33	.39
11. Pigweed	.05	.72	−.67	−.17	−.03	.19	−.23	−.11	.31
12. Cotton	.28	−.00	−.08	.53	−.06	−.52	.54	−.00	−.57
13. Watermelon	.44	−.06	−.15	.30	−.28	.10	.33	−.30	.09
14. Tomato	.16	.39	−.35	−.18	.27	.02	−.30	.19	.19
15. Pepper	−.05	−.43	.28	.44	−.58	.04	.40	−.58	.08
16. Cantaloup	−.12	.59	−.45	.12	.37	−.44	−.23	.20	−.04
17. Bean	−.56	.27	.06	−.67	.42	−.09	−.55	.43	−.23
18. Onion	.24	.54	−.50	−.61	.49	.47	−.62	.57	−.20
19. Lettuce	.54	.59	−.29	−.01	−.06	−.24	.08	.00	−.22

[1] Crops are in ascending order of water content, corresponding with figure 3. Wheat is not included.

[2] Correlation coefficients underscored equal or exceed ± 0.775.

pigweed, and tomato leaves had negative coefficients that exceeded −0.775 for the correlation between light reflectance and percent leaf-water content at 1,450-, 1,650-, and 2,200-nm; 550- and 1,450-nm.; 1,450-nm.; and 1,450- and 2,200-nm. wavelengths, respectively. In general, largest coefficients were obtained at the 1,450-nm. water-absorption band, the 1,650-nm. peak following the 1,450-nm. water-absorption band, and the 2,200-nm. peak following the 1,950-nm. water-absorption band. As percent water in the leaves increased, reflectance decreased over the 1,350- to 2,500-nm. wavelength interval. No coefficients exceeded ± 0.775 for correlations either of leaf transmittance or absorptance with percent leaf-water content.

The coefficients for correlations of light reflectance, transmittance, and absorptance with leaf thickness for the 10 leaves of each crop are given in table 6. Considering the correlations of reflectance and transmittance with leaf thickness, soybean was the only crop that had positive coefficients exceeding 0.775

transmittance (T), and absorptance (A) of light at seven upper leaf surfaces of 19 crops

Correlation coefficients [2]											
1,450 nm.			1,650 nm.			1,950 nm.			2,200 nm.		
R	T	A	R	T	A	R	T	A	R	T	A
0.43	0.39	−0.41	0.52	0.39	−0.47	0.51	0.43	−0.47	0.61	0.48	−0.53
−.25	.48	−.38	−.29	.60	−.44	−.06	.41	−.55	−.11	.59	−.54
.22	.38	−.35	.04	.35	−.32	.39	.42	−.43	.25	.50	−.49
−.93	−.43	.75	−.91	−.01	.61	−.80	−.67	.76	−.92	−.22	.58
−.78	−.34	.59	−.72	−.01	.51	−.74	−.46	.59	−.75	−.21	.51
−.67	−.47	.72	−.57	−.21	.55	−.59	−.58	.72	−.64	−.33	.61
−.73	−.34	.57	−.59	−.21	.49	−.32	−.44	.49	−.55	−.21	.38
−.25	−.59	.56	−.20	−.44	.48	−.01	−.59	.57	−.15	−.48	.46
−.69	−.41	.58	−.67	−.23	.51	−.56	−.51	.58	−.68	−.33	.52
−.44	−.31	.35	−.20	−.32	.39	−.27	−.30	.30	−.46	−.31	.35
−.80	−.50	.68	−.68	−.31	.56	−.62	−.64	.71	−.70	−.36	.53
.26	.01	−.11	.51	.07	−.30	−.17	.05	.05	.34	.11	−.21
.19	−.27	.18	.39	−.25	.09	.28	−.18	.10	.39	−.20	.07
−.81	−.16	.50	−.72	−.01	.45	−.56	−.31	.51	−.77	−.06	.39
−.18	−.70	.62	.26	−.66	.44	−.18	−.70	.65	−.03	−.67	.57
−.74	−.46	.64	−.59	−.36	.54	−.54	−.48	.68	−.64	−.41	.54
.34	.56	−.51	.41	.54	−.55	.05	.49	−.37	.46	.56	−.56
−.58	−.02	.22	−.65	.06	.25	−.34	−.29	.34	−.59	−.00	.19
.22	.13	−.15	.15	.10	−.11	.40	.22	−.56	.22	.13	−.12

TABLE 6.—*Coefficients for correlation of reflectance (R), surfaces of light at seven wavelengths*

Crop [1]	Correlation coefficients [2]								
	550 nm.			800 nm.			1,000 nm.		
	R	T	A	R	T	A	R	T	A
1. Soybean	0.78	−0.65	−0.03	0.85	−0.89	0.31	0.84	−0.92	0.52
2. Peach	.45	−.40	.01	.54	−.29	−.12	.50	−.35	−.01
3. Pumpkin	.30	−.26	−.19	−.06	−.33	.29	.02	−.27	.20
4. Pigweed	.61	.25	−.42	.64	−.35	−.17	.59	−.40	−.06
5. Okra	.34	.03	−.23	.46	.22	−.67	.46	.17	−.61
6. Corn	−.44	−.48	.58	.41	−.24	−.58	.42	−.28	−.50
7. Pepper	.13	−.34	.13	.59	−.44	−.25	.56	−.48	−.18
8. Cotton	−.39	−.25	.37	.38	−.22	−.07	.34	−.23	−.01
9. Watermelon	−.23	−.68	.70	.40	−.57	.45	.34	−.53	.43
10. Orange	−.24	−.47	.66	.12	−.68	.63	.15	−.69	.60
11. Sugarcane	−.09	−.27	.24	.28	.17	−.46	.23	.14	−.40
12. Avocado	−.08	−.62	.56	.56	−.56	−.26	.58	−.52	−.36
13. Tomato	.28	−.34	.12	.54	−.44	−.37	.43	−.47	−.12
14. Bean	.23	−.51	.27	−.35	−.61	.40	.16	−.63	.72
15. Sorghum	−.54	−.24	.39	.01	.48	−.46	.00	.46	−.43
16. Sunflower	.23	.18	−.22	.05	−.04	.01	−.02	−.04	.06
17. Cantaloup	.73	.05	−.33	.25	−.04	−.14	.23	−.19	.03
18. Lettuce	.30	.08	−.17	−.00	.11	−.07	−.29	−.11	.29
19. Onion	−.04	−.29	.20	.02	−.27	.38	−.07	.28	−.28

[1] Crops are in ascending order of leaf thickness, corresponding with figure 4. Wheat is not included.

[2] Correlation coefficients underscored equal or exceed ± 0.775.

at the 550-, 800-, and 1,000-nm. wavelengths, and a negative coefficient for transmittance exceeding −0.775 at the 1,000-nm. wavelength. The reason for this is unknown. It seems plausible, however, that leaf anatomy or cellular configuration is involved; figure 1 shows that a mature soybean leaf has a very porous mesophyll, with few spongy parenchyma cells compared with the other crop leaves. Soybean leaves also had high negative coefficients for reflectance at the 1,450-, 1,950-, and 2,200-nm. wavelengths and for transmittance at the 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths. Peach, pigweed, tomato, bean, and onion crops also had high negative correlation coefficients for transmittance at two or more of the 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths. These wavelengths are within the water-absorption spectral range (1,350- to 2,500-nm. wavelength interval), and as leaf-water content increased, light reflectance and transmittance decreased and absorptance increased. High positive coefficients were obtained for the correlation between leaf *transmittance (T), and absorptance (A) by upper leaf upper leaf surfaces of 19 crops*

Correlation coefficients [2]											
1,450 nm.			1,650 nm.			1,950 nm.			2,200 nm.		
R	T	A	R	T	A	R	T	A	R	T	A
−0.80	−0.93	0.92	0.49	−0.92	0.89	−0.78	−0.93	0.91	−0.78	−0.94	0.93
−.66	−.82	.83	−.27	−.73	.75	−.67	−.85	.83	−.60	−.82	.82
.04	−.10	.06	.08	−.15	.08	.17	−.10	.04	.02	−.17	.14
−.61	−.81	.83	−.09	−.66	.67	−.54	−.86	.86	−.52	−.80	.85
−.08	−.07	.08	.17	.06	−.13	−.18	−.12	.16	−.05	−.05	.06
−.40	−.75	.68	−.10	−.60	.58	−.41	−.76	.69	−.36	−.72	.68
−.41	−.57	.61	.19	−.55	.38	−.23	−.64	.62	−.25	−.59	.59
−.48	−.41	.50	−.19	−.31	.37	−.71	−.48	.65	−.48	−.34	.44
−.33	−.52	.55	−.00	−.56	.60	−.33	−.53	.57	−.42	−.58	.64
−.09	−.52	.63	−.01	−.65	.67	−.08	−.39	.67	−.13	−.59	.66
−.54	−.26	.44	−.33	−.10	.29	−.25	−.33	.33	−.46	−.19	.35
−.59	−.66	.66	−.49	−.67	.69	−.41	−.69	.66	−.68	−.69	.70
−.54	−.81	.82	−.23	−.69	.68	−.13	−.80	.59	−.50	−.73	.77
−.61	−.77	.77	−.71	−.73	.79	−.52	−.81	.79	−.70	−.78	.80
−.36	−.03	.22	−.26	.19	−.00	−.33	−.14	.26	−.38	.02	.17
−.63	−.16	.40	−.58	−.11	.40	−.02	−.23	.21	−.57	−.14	.32
−.33	−.77	.68	−.47	−.65	.72	.35	−.77	.31	−.46	−.76	.74
−.43	−.42	.52	−.50	−.41	.52	−.41	−.40	.46	−.45	−.42	.51
−.23	−.89	.90	−.37	−.86	.92	.05	.03	−.05	−.23	−.89	.92

thickness and percent light absorptance for the soybean, peach, pigweed, bean, and onion crops at three or more of the 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths.

It was thought that the amount of water in the leaf tissue that was placed over the port of the spectrophotometer might have influenced the spectral energy measurements. Accordingly, grams of water per cubic centimeter of leaf tissue was calculated for each crop leaf used in this study, except for wheat. Coefficients for the correlations of grams of water per cubic centimeter of leaf tissue with reflectance, transmittance, and absorptance are given in table 7. There was no correlation between reflectance and grams of water per cubic centimeter of leaf tissue. With transmittance, coefficients above 0.775 occurred only with okra leaves at 1,000-, 1,450-, 1,650-, 1,950-, and 2,200-nm. wavelengths. The correlation between absorptance and grams of water per cubic centimeter of leaf tissue gave high positive coefficients for okra leaves at 1,450, 1,650, and 2,200 nm. Variability in grams

TABLE 7.—*Coefficients for correlation of reflectance (R), trans at seven wavelengths with grams of water per*

Crop [1]	Correlation coefficients [2]								
	550 nm.			800 nm.			1,000 nm.		
	R	T	A	R	T	A	R	T	A
1. Cotton	−0.33	0.24	−0.14	−0.32	0.13	0.15	−0.31	0.10	0.17
2. Pepper	−.31	−.17	.26	−.42	.12	.36	−.45	.14	.34
3. Corn	−.49	.25	−.07	−.53	.57	.04	−.53	.55	.10
4. Tomato	−.08	.47	−.30	−.54	.33	.47	−.42	.41	.15
5. Cantaloup	−.63	−.02	.27	−.06	.22	−.17	−.25	.24	−.07
6. Pumpkin	.64	−.08	−.36	−.16	−.42	.42	−.19	−.44	.49
7. Sorghum	−.56	−.46	.54	−.03	.05	−.02	−.09	.03	.06
8. Watermelon	.55	−.45	.14	.39	−.53	.39	.41	−.56	.41
9. Soybean	−.37	.29	.04	−.32	.56	−.50	−.25	.56	−.64
10. Bean	−.23	.15	.00	−.29	.26	−.14	−.15	.29	−.28
11. Orange	.19	−.18	−.05	−.08	−.43	.52	−.09	−.45	.55
12. Sugarcane	.14	.40	−.36	−.34	.44	−.21	−.38	.40	−.08
13. Sunflower	.55	.19	−.32	.12	−.27	.22	.10	−.30	.26
14. Pigweed	.04	−.55	.48	.65	−.43	−.08	.62	−.39	−.08
15. Avocado	.11	−.16	.09	.19	−.14	−.17	.18	−.22	−.02
16. Okra	−.29	−.40	.49	.31	−.73	.34	.26	−<u>.78</u>	.48
17. Peach	−.49	.43	.06	−.53	.67	−.31	−.52	.70	−.36
18. Lettuce	.26	.24	−.25	−.22	−.31	.39	−.49	−.50	.69
19. Onion	−.42	.19	−.06	−.22	.06	.35	−.23	.14	.01

[1] Crops are arranged in ascending order of grams of water per cubic centimeter of leaf tissue. Wheat is not included.

[2] Correlation coefficients underscored equal or exceed ± 0.775.

of water per cubic centimeter among okra leaves had an important influence on their light absorptance and transmittance, compared with the variability among leaves of the other crops.

Optical and geometrical leaf parameters

The flat-plate model (*2*) for calculation of effective optical constants of leaves has been applied to leaves of the 20 crops. All available values of reflectance and transmittance for the leaves of 20 crops were reduced to average values $\bar{a}$, $\bar{b}$ at the 41 wavelengths 0.50, 0.55, . . . , 2.50 μ. Optical parameters a, b are defined elsewhere (*4*). Thirteen data points in the vicinity of plant pigment and water-absorption bands were deleted in advance (wavelengths 0.50, 0.55, 0.60, 0.65, 0.70, 1.40, 1.45, 1.50, 1.90, 1.95, 2.00, 2.45, and 2.50 μ) from calculations of refractive indices, *n*. Such editing is justified because determination of the index of refraction n is weak in the vicinity of absorption bands.

mittance (T), and absorptance (A) by upper leaf surfaces of light cubic centimeter of leaf tissue of 19 crops

Correlation coefficients [1]											
1,450 nm.			1,650 nm.			1,950 nm.			2,200 nm.		
R	T	A	R	T	A	R	T	A	R	T	A
−0.41	−0.09	0.23	−0.44	−0.07	0.26	−0.14	−0.07	0.11	−0.39	−0.10	0.22
.11	.10	−.13	−.21	.12	.02	−.08	.16	−.10	.05	.12	−.12
−.53	−.02	.26	−.63	.27	.21	−.50	−.17	.30	−.59	.07	.23
−.12	.42	−.23	−.26	.41	−.16	−.26	.33	−.07	−.15	.40	−.22
−.61	.02	.24	−.39	−.00	.17	−.72	.16	.36	−.46	−.02	.19
.03	−.60	.46	−.04	−.53	.48	.36	−.52	.37	.11	−.50	.38
−.16	−.35	.34	−.17	−.19	.28	−.09	−.40	.36	−.14	−.32	.35
−.05	−.64	.57	.28	−.59	.50	.17	−.59	.50	.10	−.60	.51
.53	.56	−.56	−.01	.55	−.59	.43	.57	−.54	.46	.55	−.55
.35	.39	−.40	.45	.38	−.43	.22	.37	−.36	.47	.42	−.46
−.20	−.49	.65	−.24	−.44	.60	.23	−.51	.52	−.21	−.48	.58
−.69	−.31	.55	−.63	.02	.40	−.62	−.48	.57	−.69	−.15	.42
−.34	−.66	.62	−.22	−.61	.64	.07	−.64	.54	−.33	−.64	.62
.25	−.28	.11	.52	−.36	.15	.16	−.11	.04	.20	−.33	.22
−.22	−.21	.22	.05	− 19	.14	−.25	−.17	.20	−.06	−.15	.13
−.54	−.86	.80	−.38	−.86	.83	−.28	−.81	.68	−.54	−.85	.82
.13	.59	−.46	−.06	.71	−.58	.44	.52	−.52	.27	.68	−.61
.57	−.66	.78	−.70	−.70	.82	−.45	−.22	.48	-.60	−.67	.77
−.36	.19	−.05	−.25	.17	−.03	.07	−.24	−.07	−.29	.18	−.08

Figures 7*A* through 7*T* display the 95-percent confidence bands of the dispersion curves. Computational and statistical procedures used have appeared elsewhere (*1, 3, 10*). Statistically, 95 percent of experimental points fall within the confidence limits. The dispersion curves of figures 7*A* through 7*T*, assumed to be cubics wavelength λ, are expressed by the relation

$$n = \Sigma a_i \lambda^i, \qquad (1)$$

where the coefficients $a_0, \ldots, a_3$ were determined by regression. Table 8 contains the coefficients of equation 1 for all data discussed.

The dispersion curves of most of the leaves illustrated in figure 7 are remarkably similar. With the exceptions of onion (*H*), pigweed (*L*), and lettuce (*F*), the dispersion curves are characterized by similar shapes and relatively close confidence bands. For the exceptions mentioned, the flat-plate model (*2*) appears not to apply. However, the onion, pigweed, and lettuce leaves

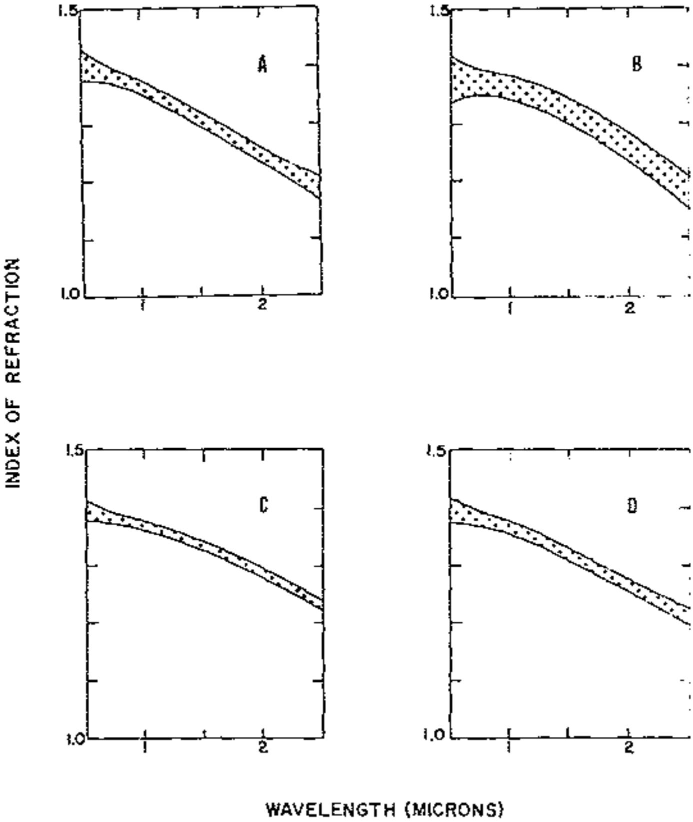

FIGURE 7.—Dispersion curves of light over the 500- to 2,500-nm. wavelength interval for leaves of 20 crops by index of refraction, showing confidence bands. *A*, avocado; *B*, bean; *C*, cantaloup; *D*, corn; *E*, cotton; *F*, lettuce; *G*, okra; *H*, onion; *I*, orange; *J*, peach; *K*, pepper; *L*, pigweed; *M*, pumpkin; *N*, sorghum; *O*, soybean; *P*, sugarcane; *Q*, sunflower; *R*, tomato; *S*, watermelon; and *T*, wheat.

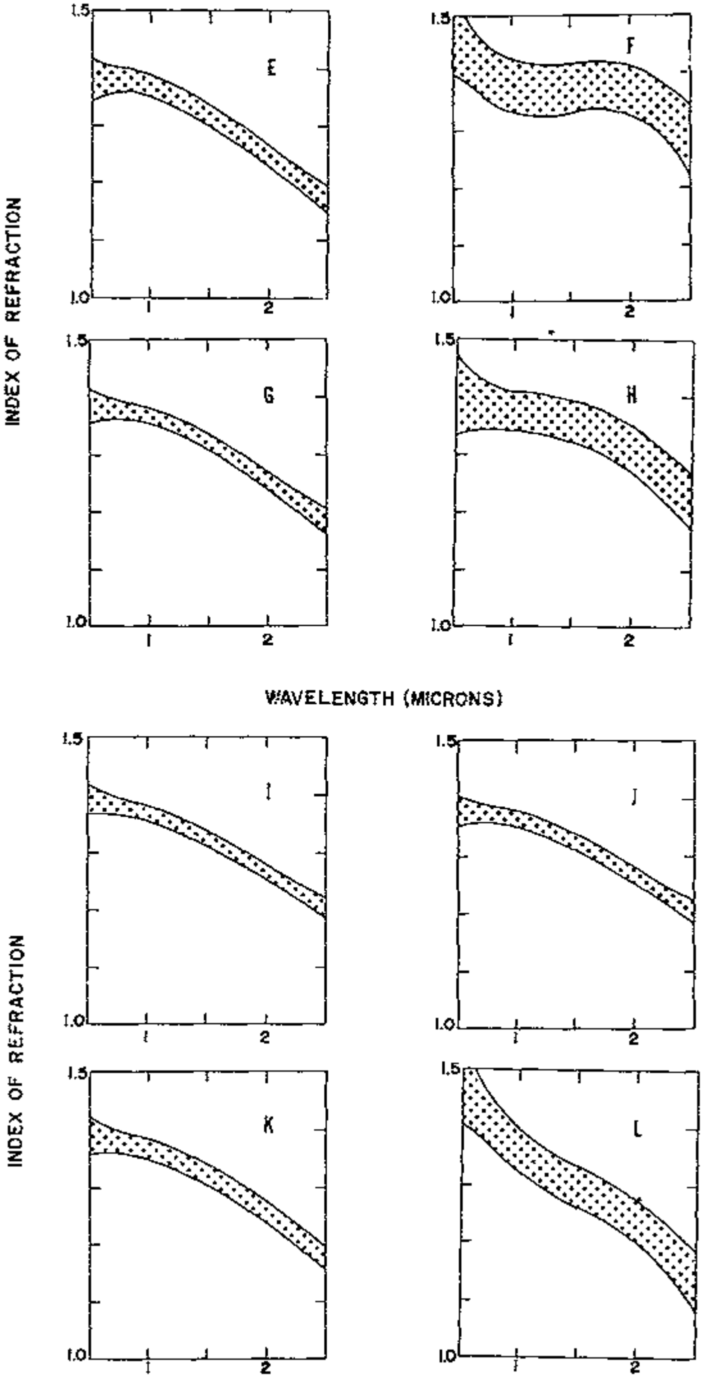

FIGURE 7.—Continued.

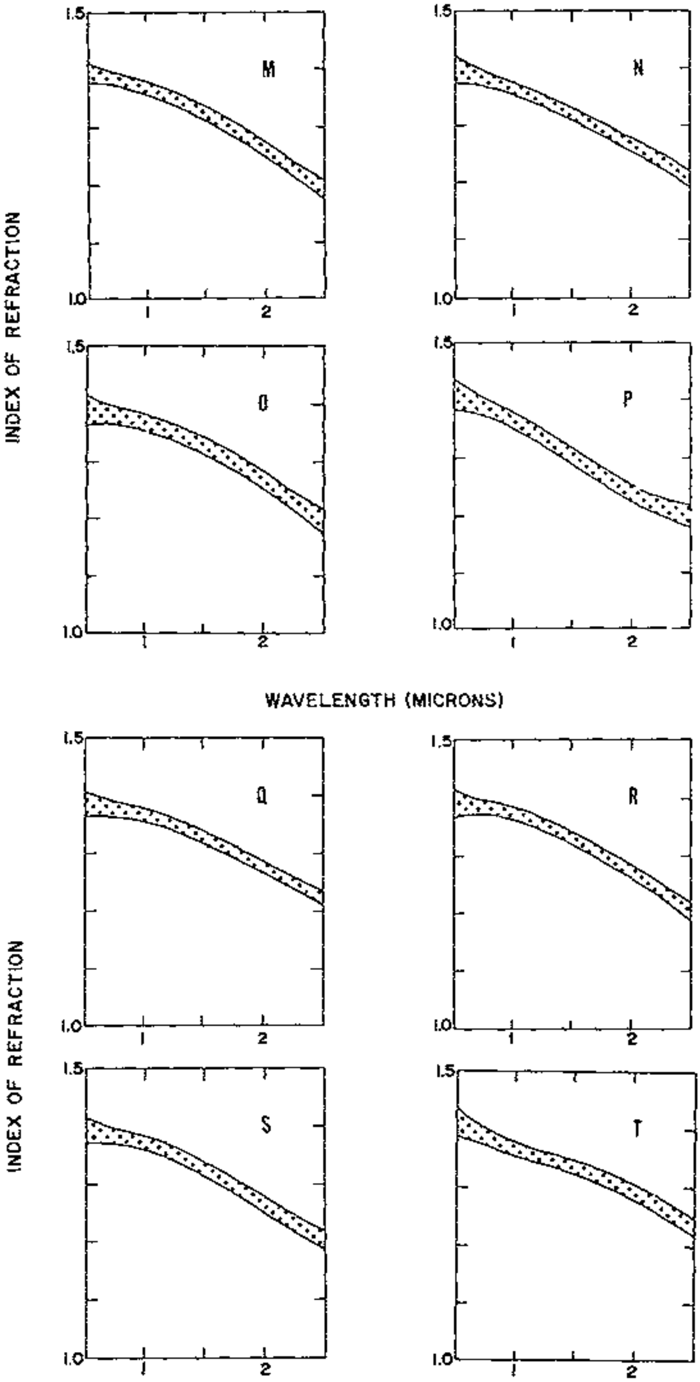

FIGURE 7.—Continued.

TABLE 8.—*Coefficients of dispersion curve $n = \Sigma a_i \lambda^i$ for leaves of 20 crops, where λ is expressed in microns*

Crop	a_0	a_1	a_2	a_3
	Microns	*Microns*	*Microns*	*Microns*
Avocado	1.398	0.063	−0.120	0.025
Bean	1.365	.059	−.067	.006
Cantaloup	1.425	−.062	.013	−.008
Corn	1.403	.017	−.065	.011
Cotton	1.320	.196	−.177	.030
Lettuce	1.792	−.878	.587	−.127
Okra	1.347	.134	−.134	.022
Onion	1.481	−.217	.156	−.044
Orange	1.390	.037	−.071	.010
Peach	1.347	.117	−.115	.018
Pepper	1.393	.005	−.031	−.003
Pigweed	1.721	−.628	.334	−.071
Pumpkin	1.406	.011	−.058	.007
Sorghum	1.408	.004	−.055	.009
Soybean	1.394	.003	−.033	.127
Sugarcane	1.402	.079	−.145	.032
Sunflower	1.355	.110	−.116	.020
Tomato	1.379	.062	−.078	.010
Watermelon	1.377	.076	−.098	.016
Wheat	1.487	−.185	.085	−.021

were different from the other crop leaves—only one-half of the tubular onion leaves was used, lettuce leaves were immature, and veins of pigweed leaves (fig. 1) are surrounded by large, cubical, parenchymatous cells.

Table 9 includes the leaf parameters that relate to the amount of water and air in the leaf. As explained previously (*1, 2, 3*), the quantity D in the flat-plate model is the equivalent thickness of pure water necessary to produce the light absorption observed in the leaf. The quantity N in the model is the number of compact layers into which D must be subdivided in order to achieve the observed partition of energy between reflectance and transmittance. The infinite reflectance R_{∞} at 1.65 μ (*4*), produced by leaves piled sufficiently deep, is listed in column 5 of table 9. The quantity R_{∞} can be measured directly; the number listed in table 9, however, is a calculated value obtained by techniques previously described (4). The entries of table 9 were obtained by adjusting the quantity D, over the spectral range 1.4 to 2.5 μ, to achieve the best fit of the leaf absorption k to the absorption k_o for pure water. Column 6 of table 9 is the standard error (S.E.) calculated from the relation

$$S.E. = \{\Sigma[\log (k/k_o)]^2/[n(n-1)]\}^{1/2}. \qquad (2)$$

The summation in equation 2 includes the 23 values at 0.05-μ intervals over the range 1.4 to 2.5 μ. This quantity S.E. can be considered a figure of merit, because S.E. would vanish entirely if the model were exact and the material were water. The quantities D and S.E. in table 9 are positively correlated ($r = 0.728$).

As indicated previously (*1, 2, 3*), the quantities D/N and R_{∞} are strongly correlated. Figure 8 indicates the relationship. The quantity D and the leaf thickness are also correlated with R_{∞}. The thinner the leaf, the greater will be reflectance produced by a pile of such leaves. This fact has important implications in the interpretation of remote-sensing data.

TABLE 9.—*Parameters that specify amount of water and intercellular air space in leaves of 20 crops*

Crop	D [1]	N [2]	D/N	R_{∞} [3]	Standard error
	Microns	*Number*		*Percent*	
Avocado	190	1.73	109.3	40.8±0.7	0.022
Bean	219	2.20	99.5	46.9±0.5	.015
Cantaloup	239	1.56	152.8	37.6±0.5	.016
Corn	173	1.44	119.6	41.8±0.8	.013
Cotton	199	1.52	130.8	39.7±0.4	.016
Lettuce	524	1.05	499.7	17.6±1.5	.018
Okra	181	1.65	109.5	42.6±0.7	.017
Onion	606	1.13	533.6	18.5±0.6	.094
Orange	209	2.27	91.9	44.7±0.5	.019
Peach	119	1.65	72.0	50.3±0.5	.019
Pepper	189	1.76	107.3	44.4±0.6	.015
Pigweed	173	1.43	121.1	41.0±0.4	.017
Pumpkin	152	1.48	102.3	44.0±0.5	.017
Sorghum	101	1.51	67.0	50.7±0.7	.018
Soybean	111	1.45	76.8	50.8±1.0	.015
Sugarcane	224	1.55	144.1	36.4±0.5	.022
Sunflower	242	1.54	157.1	36.9±0.5	.017
Tomato	260	1.70	152.7	36.6±0.8	.019
Watermelon	203	1.59	127.8	39.9±0.9	.018
Wheat	169	1.82	92.4	45.6±0.8	.017

[1] Equivalent thickness in microns of pure water necessary to produce the observed leaf absorption (*1*).

[2] Number of layers into which D must be subdivided to achieve the observed partition of energy between reflectance and transmittance (*1*).

[3] Infinite reflectance at 1.65 μ wavelength.

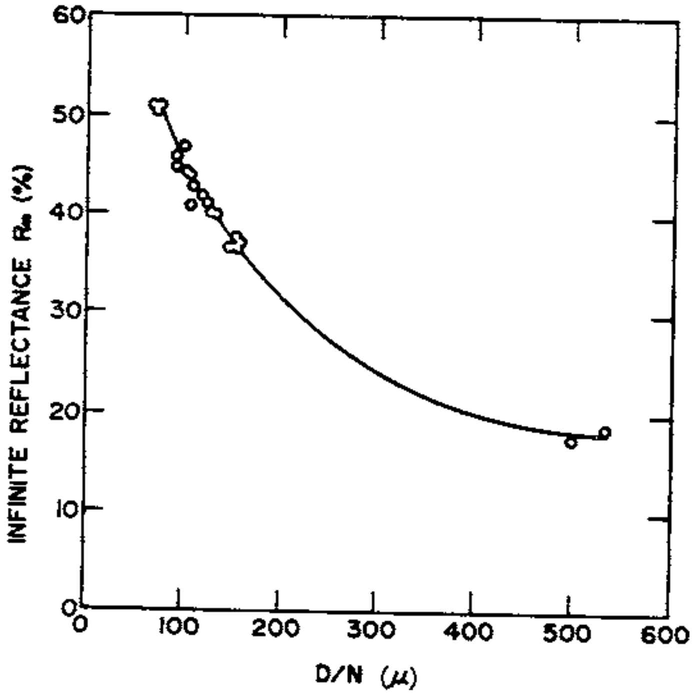

FIGURE 8.—Infinite reflectance R_∞ at 1.65 μ for 20 genera of plant leaves, plotted as a function of the characteristic linear dimension D/N.

Table 10 is a compilation of the mean absorption spectra in cm.$^{-1}$ units over the range 1.4 to 2.5 μ for the leaves of 20 crops. These values correlate (r = 0.998) with those previously obtained (*3*) on other leaves of agricultural interest. The published values for pure water are also presented in table 10 for comparison.

Figures 9 and 10 are comparisons of experimental and computed values of leaf-water thickness obtained by procedures previously discussed (*13*). The shaded portions on the bar graphs represent plus or minus one standard deviation. All data are plotted for the laboratory water determinations that were made on entire leaves. Sugarcane, corn, sorghum, and wheat leaves are not included in figures 9 and 10. Their thickness and water-content determinations in the laboratory were made on sections of entire leaves. With the exception of pumpkin, avocado, okra, tomato, cantaloup, and lettuce, there is no statistically significant difference between water obtained experimentally and water determined theoretically. However, none of the six exceptions

TABLE 10.—*Mean light absorption spectra of the leaves of 20 crops compared with those of water over the 1.4- to 2.5-μ wavelength range*

Wavelength of light	Absorption spectra	
	Leaf [1]	Water [2]
Microns	*Cm.*$^{-1}$	*Cm.*$^{-1}$
1.40	14.3± 1.0	12.5
1.45	24.6± 2.0	25.8
1.50	16.5± 1.5	18.5
1.55	9.9± .3	9.8
1.60	6.8± .3	6.5
1.65	5.6± .3	5.1
1.70	5.8± .4	5.2
1.75	7.2± .4	6.0
1.80	8.1± .3	8.1
1.85	15.5± 1.0	9.8
1.90	58.7± 6.4	81.0
1.95	77.9±18.7	106.0
2.00	49.5± 3.2	68.0
2.05	33.7± 1.9	43.0
2.10	24.2± .6	26.0
2.15	19.3± .7	19.0
2.20	17.6± .6	16.0
2.25	20.3± .8	18.0
2.30	26.4± 1.0	22.0
2.35	34.8± .7	31.0
2.40	46.3± 1.9	43.0
2.45	59.8± 1.9	60.0
2.50	70.0± 4.2	83.0

[1] Average from leaves of 20 different crops. Each kind of leaf was assigned a statistical weight of unity.

[2] Values for pure water as published by Curcio and Petty (*6*).

exhibit a highly statistically significant difference (unpaired t test) between observed and computed values for leaf water.

Table 11 includes the absorption spectra, over the 0.5- to 1.3-μ range, for 11 kinds of plant leaves (first 11 entries) reported in an earlier paper (*15*), plus the 20 (last 20 entries) crop leaves introduced in the present paper. Note that corn appears twice—once in the earlier work and again in the 20 leaves reported in this paper.

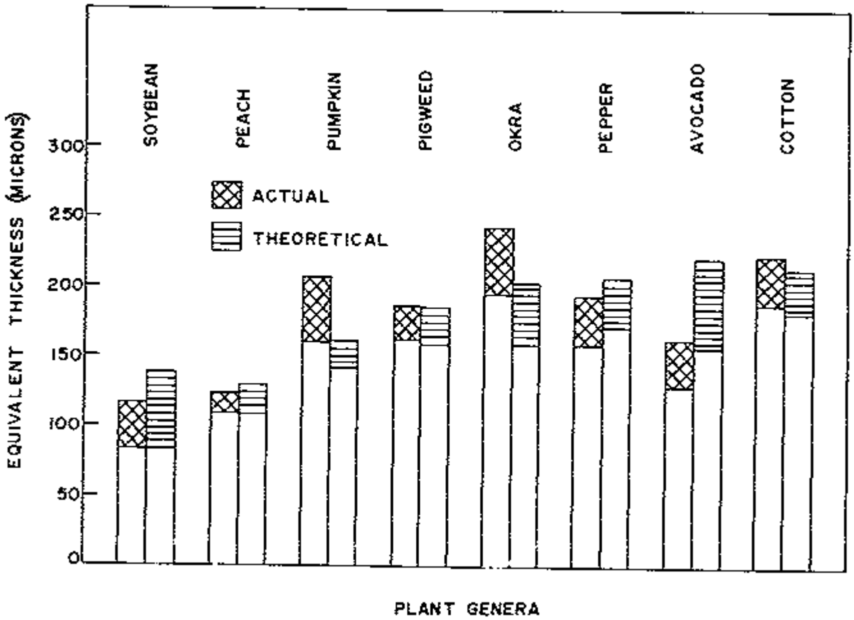

FIGURE 9.—Comparison of observed and computed values of effective water thickness of leaves. The shaded areas represent a variation of one standard deviation.

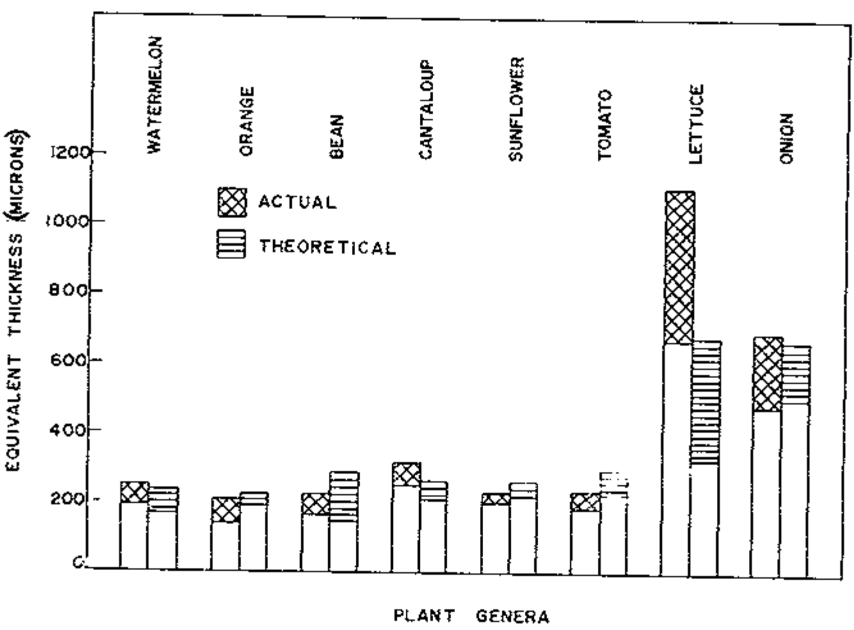

FIGURE 10.—Comparison of observed and computed values of effective water thickness of leaves. The shaded areas represent a variation of one standard deviation.

TABLE 11.—*Light-absorption spectra of 30 kinds of plant leaves over the 0.5– to 1.3–μ wavelength range*

Plant leaf[1]	Wavelength in μ								
	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
	Cm.$^{-1}$	*Cm.*$^{-1}$	*Cm.*$^{-1}$	*Cm.*$^{-1}$	*Cm.*$^{-1}$	*Cm.*$^{-1}$	*Cm.*$^{-1}$	*Cm.*$^{-1}$	*Cm.*$^{-1}$
Avocado	98.0	121.8	13.7	0.7	0.6	0.6	0.6	1.3	1.7
Banana	55.2	60.2	9.7	.4	.4	.5	.5	1.2	1.7
Bean	36.2	46.2	7.1	.1	.2	.2	.2	.9	1.6
Begonia	21.6	19.3	3.0	.2	.2	.3	.3	1.0	1.6
Cantaloup	44.4	54.3	8.3	.5	.4	.4	.5	1.1	1.8
Corn	76.2	81.7	15.7	.7	.6	.6	.5	1.2	1.7
Corn	70.2	79.1	15.0	.5	.4	.5	.5	1.2	1.7
Cotton	48.6	58.0	9.2	.5	.5	.6	.6	1.2	1.8
Crinum	29.5	29.5	4.6	.3	.3	.5	.4	1.2	1.7
Eucalyptus	56.3	61.0	9.7	.7	.6	.6	.5	1.2	1.6
Ficus	45.5	48.1	5.9	.3	.3	.4	.4	1.1	1.6
Hyacinth	42.7	47.3	7.7	.4	.3	.4	.3	1.0	1.6
Lettuce	2.6	2.7	1.0	.4	.5	.6	.6	1.6	2.3
Ligustrum	44.9	48.7	5.7	.3	.3	.4	.4	1.1	1.5
Okra	54.7	61.8	11.2	.7	.6	.6	.6	1.3	1.8
Oleander	54.7	57.6	9.7	.8	.7	.8	.7	1.4	1.7
Onion	13.4	15.6	2.8	.2	.2	.4	.4	1.1	1.7
Orange	103.6	121.3	14.4	.8	.8	.7	.7	1.4	1.8
Peach	112.1	137.1	17.0	.7	.7	.6	.6	1.2	1.7
Pepper	46.3	53.5	8.8	.3	.3	.3	.3	1.0	1.6
Pigweed	54.7	78.3	13.5	.4	.4	.4	.4	1.1	1.7
Pumpkin	74.2	84.7	13.4	.9	.7	.7	.6	1.3	1.8
Rose	108.1	128.8	18.9	.6	.5	.5	.5	1.0	1.5
Sedum	10.4	10.2	2.0	.1	.1	.3	.2	1.0	1.5
Sorghum	82.6	102.1	20.8	.9	.7	.7	.6	1.3	1.8
Soybean	74.5	91.4	15.0	.5	.4	.4	.4	1.1	1.6
Sugarcane	30.2	37.0	8.4	.8	.8	.9	.9	1.6	2.1
Sunflower	45.0	50.6	8.6	.5	.5	.5	.5	1.1	1.7
Tomato	59.2	82.0	9.2	.9	.8	.8	.8	1.4	2.1
Watermelon	52.0	62.0	8.7	.9	.8	.7	.7	1.4	2.0
Wheat	105.7	108.3	16.3	.8	.7	.7	.6	1.3	1.8

[1] Data for the following 11 entries have previously been reported by Gausman and others (*15*): Banana, begonia, corn, crinum, eucalyptus, ficus, hyacinth, ligustrum, oleander, rose, and sedum.

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Appendix

TABLE 12.—*Average percent light reflectance of upper leaf surfaces of 10 leaves for each of 20 crops for 41 wavelengths over the 500– to 2,500–nm. wavelength interval*

Crop	Reflectance of light at wavelengths of—										
	500 nm.	550 nm.	600 nm.	650 nm.	700 nm.	750 nm.	800 nm.	850 nm.	900 nm.	950 nm.	1,000 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	8.2	8.9	6.8	7.2	26.6	47.9	50.4	50.3	50.1	49.4	49.7
Bean	15.2	18.5	12.0	10.7	37.3	55.7	56.9	56.9	56.5	55.8	56.2
Cantaloup	11.6	12.7	10.0	9.9	28.6	46.1	47.7	47.7	47.5	46.8	47.3
Corn	12.7	16.2	12.0	9.3	24.8	45.4	46.3	46.4	46.2	45.5	45.7
Cotton	9.8	11.8	8.0	7.7	28.6	45.8	47.2	47.2	46.9	46.2	46.6
Lettuce	27.6	30.3	26.8	23.6	33.7	37.6	37.6	37.5	36.7	34.6	35.3
Okra	10.8	12.9	9.5	9.2	29.0	47.2	49.0	49.2	49.0	48.4	48.7
Onion	10.1	11.6	8.5	8.1	25.0	39.4	40.5	40.4	39.6	37.7	38.5
Orange	8.9	10.2	7.2	7.1	28.9	53.2	55.8	55.9	55.7	55.2	55.6
Peach	9.6	10.9	8.3	8.6	29.1	47.7	49.5	49.5	49.3	49.0	49.3
Pepper	12.8	16.8	11.0	9.3	32.8	50.5	51.6	51.6	51.4	50.7	51.0
Pigweed	10.9	12.4	9.3	9.0	26.6	43.9	45.7	45.5	45.4	44.8	45.1
Pumpkin	10.2	11.8	8.9	10.6	29.1	44.9	46.4	46.3	46.2	45.8	46.7
Sorghum	15.0	17.2	13.3	11.3	28.2	45.8	47.3	47.4	47.3	46.9	47.0
Soybean	10.9	13.1	8.7	7.9	28.8	45.6	46.6	46.5	46.3	45.9	46.0
Sugarcane	15.9	18.6	13.4	11.4	29.9	45.8	46.9	46.8	46.4	45.6	45.7
Sunflower	9.6	11.0	8.4	8.5	27.5	45.4	47.3	47.3	47.1	46.5	46.9
Tomato	10.0	11.1	8.6	8.6	25.9	46.6	48.4	48.6	48.5	47.8	48.3
Watermelon	11.9	14.4	10.7	9.9	30.4	45.6	46.8	47.0	47.0	46.3	46.8
Wheat	10.3	13.4	9.6	7.7	27.3	50.2	51.5	51.7	51.4	51.0	51.2

Crop	Reflectance of light at wavelengths of—									
	1,050 nm.	1,100 nm.	1,150 nm.	1,200 nm.	1,250 nm.	1,300 nm.	1,350 nm.	1,400 nm.	1,450 nm.	1,500 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	49.7	49.3	47.1	46.8	47.1	45.2	41.0	26.3	19.2	23.1
Bean	56.6	56.0	53.6	53.5	53.6	50.8	44.9	25.6	18.5	24.6
Cantaloup	47.6	47.0	44.6	44.3	44.5	41.9	36.7	20.6	14.8	19.1
Corn	46.0	45.5	43.3	43.2	43.5	41.8	38.3	23.4	16.8	21.0
Cotton	47.0	46.4	44.2	44.0	44.2	42.0	37.5	21.7	15.2	19.6
Lettuce	36.3	35.0	30.3	29.6	29.8	26.4	21.4	11.8	9.1	10.4
Okra	49.0	48.5	46.6	46.2	46.4	44.5	40.4	25.6	18.1	22.3
Onion	39.4	38.2	33.3	32.5	32.9	29.0	23.0	10.3	6.8	8.4
Orange	55.7	55.4	53.1	52.8	53.0	51.2	47.1	31.2	22.3	26.6
Peach	49.4	49.1	47.7	47.7	47.8	46.5	43.0	30.3	24.3	28.8
Pepper	51.4	40.8	48.5	48.4	48.6	46.4	41.7	25.0	17.6	22.6
Pigweed	45.1	44.6	42.8	42.5	42.6	40.6	36.2	21.5	15.6	19.9
Pumpkin	46.2	45.7	44.2	44.0	44.0	42.1	37.4	24.6	19.0	23.6
Sorghum	47.0	46.8	45.5	45.3	45.4	44.3	41.7	30.9	24.7	28.2
Soybean	46.2	45.8	44.5	44.5	44.4	43.1	40.1	27.7	21.8	26.1
Sugarcane	46.0	45.4	42.9	42.6	42.7	40.5	35.9	20.7	14.4	18.3
Sunflower	47.2	46.6	44.1	44.0	44.2	41.7	36.4	20.4	14.3	18.4
Tomato	48.6	48.0	45.4	45.2	45.4	42.7	37.3	20.5	14.4	18.9
Watermelon	47.2	46.6	44.5	44.4	44.5	42.2	37.5	22.0	16.6	21.2
Wheat	51.5	51.0	48.9	48.8	49.2	47.2	43.5	27.7	21.7	26.5

TABLE 12.—*Average percent light reflectance of upper leaf surfaces of 10 leaves for each of 20 crops for 41 wavelengths over the 500- to 2,500-nm. wavelength interval*—Continued

Crop	Reflectance of light at wavelengths of—									
	1,550 nm.	1,600 nm.	1,650 nm.	1,700 nm.	1,750 nm.	1,800 nm.	1,850 nm.	1,900 nm.	1,950 nm.	2,000 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	29.0	32.5	34.1	33.2	31.2	30.3	23.1	9.7	7.5	10.2
Bean	33.1	38.4	40.9	40.6	37.5	35.2	24.2	8.0	6.0	9.4
Cantaloup	25.5	29.9	32.0	31.5	28.9	27.4	19.4	8.1	6.9	8.6
Corn	27.1	31.0	32.9	32.6	30.1	28.8	23.1	7.9	7.2	9.7
Cotton	26.2	30.4	32.3	31.9	29.4	27.9	19.9	7.6	6.0	7.9
Lettuce	13.0	15.4	16.8	16.8	15.0	13.8	10.6	6.2	5.6	6.4
Okra	28.8	33.0	35.0	34.5	32.3	30.8	23.0	9.4	7.0	9.4
Onion	12.0	15.1	17.2	17.0	14.6	13.1	9.4	4.9	4.4	4.9
Orange	33.3	37.6	39.8	39.0	36.6	35.4	27.8	11.4	8.6	12.0
Peach	34.3	37.5	38.9	38.0	36.4	35.6	27.4	12.5	10.5	14.4
Pepper	30.0	34.7	36.9	36.6	33.9	32.2	23.4	8.5	6.6	9.4
Pigweed	26.1	30.0	31.8	31.3	29.1	27.6	19.5	7.7	5.8	8.0
Pumpkin	29.2	32.6	34.6	33.1	31.3	29.5	21.6	9.0	7.1	10.6
Sorghum	33.2	36.1	37.4	36.9	35.3	34.2	28.2	14.1	12.0	15.6
Soybean	31.9	35.2	36.6	36.3	34.5	33.3	25.5	10.2	8.1	12.1
Sugarcane	24.2	28.0	30.4	30.0	27.5	25.9	18.8	7.6	6.2	8.2
Sunflower	24.9	29.3	31.3	30.5	28.1	26.6	18.9	8.0	6.5	8.1
Tomato	25.6	30.0	32.1	31.7	28.9	27.3	19.1	7.3	6.0	7.9
Watermelon	27.4	31.2	33.0	32.4	29.9	28.7	20.5	8.0	6.9	9.1
Wheat	32.7	36.4	38.2	37.4	35.2	34.3	27.3	9.7	9.0	12.8

Crop	Reflectance of light at wavelengths of—									
	2,050 nm.	2,100 nm.	2,150 nm.	2,200 nm.	2,250 nm.	2,300 nm.	2,350 nm.	2,400 nm.	2,450 nm.	2,500 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	13.2	15.7	18.1	19.5	17.4	14.2	11.6	9.5	7.8	7.0
Bean	14.1	18.9	22.6	24.0	21.5	17.2	12.8	9.5	7.2	5.9
Cantaloup	11.1	14.2	16.5	17.5	15.7	12.6	9.9	8.0	6.6	6.0
Corn	12.6	15.8	18.3	19.8	17.6	14.4	11.6	9.3	7.5	6.7
Cotton	10.8	14.1	16.7	16.8	15.8	12.5	9.8	7.5	6.0	5.3
Lettuce	7.4	8.4	9.2	9.4	8.8	7.7	6.6	5.8	5.2	4.9
Okra	12.8	16.3	19.0	20.2	18.3	14.9	11.8	9.3	7.3	6.5
Onion	5.6	6.6	7.6	8.0	7.4	6.3	5.4	4.8	4.6	4.5
Orange	15.8	19.2	22.1	23.6	21.2	17.4	14.1	11.1	9.0	7.8
Peach	18.3	21.6	24.3	25.7	23.1	19.3	16.0	13.2	10.7	9.5
Pepper	13.2	17.1	20.2	21.5	19.3	15.4	11.7	8.9	6.8	5.7
Pigweed	11.0	14.3	16.8	17.8	15.9	12.9	9.9	7.6	5.9	5.1
Pumpkin	14.0	17.2	19.5	20.9	18.2	14.9	12.1	9.6	7.6	7.0
Sorghum	19.1	22.1	24.5	25.8	23.7	20.4	17.4	14.7	12.4	11.3
Soybean	16.6	20.6	23.5	24.8	22.7	19.1	15.4	12.1	9.5	8.2
Sugarcane	10.5	13.1	15.5	16.4	14.5	11.8	9.5	7.8	6.5	6.0
Sunflower	10.4	13.2	15.4	16.2	14.4	11.6	9.3	7.6	6.5	6.0
Tomato	10.7	13.7	16.3	17.3	15.3	12.2	9.5	7.4	6.0	5.4
Watermelon	12.1	15.3	17.7	18.8	16.8	13.5	10.8	8.5	6.9	6.2
Wheat	16.6	20.2	22.6	24.4	21.7	18.2	15.0	12.2	9.7	8.5

TABLE 13.—*Average percent light transmittance of upper leaf surfaces of 10 leaves for each of 20 crops for 41 wavelengths over the 500– to 2,500–nm. wavelength interval*

Crop	Transmittance of light at wavelengths of—										
	500 nm.	550 nm.	600 nm.	650 nm.	700 nm.	750 nm.	800 nm.	350 nm.	900 nm.	950 nm.	1,000 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	2.3	4.1	1.4	3.1	24.9	42.4	44.8	45.4	45.5	45.5	46.1
Bean	6.9	10.9	5.5	3.6	26.6	40.9	42.0	42.2	42.0	41.5	42.2
Cantaloup	4.9	8.7	3.9	2.4	27.5	46.3	48.1	48.6	48.6	48.0	48.8
Corn	3.7	9.8	3.7	.7	22.6	48.9	50.5	50.9	51.1	50.7	51.2
Cotton	8.1	13.1	7.0	4.2	30.6	47.8	49.1	49.4	49.3	39.0	49.4
Lettuce	38.4	44.3	39.5	34.0	49.5	55.3	55.6	55.5	54.8	52.6	53.7
Okra	5.9	14.8	5.8	4.1	27.1	44.6	46.4	46.7	46.9	46.7	47.3
Onion	11.7	18.8	10.8	6.6	35.8	54.3	55.7	55.7	55.0	52.9	54.0
Orange	.7	1.9	.5	.5	17.6	36.0	38.2	38.6	38.6	38.4	33.9
Peach	3.5	6.2	2.6	2.8	27.1	45.5	47.3	47.6	47.7	47.6	47.9
Pepper	6.9	12.6	6.4	3.1	28.4	44.8	46.2	46.5	46.4	46.0	46.5
Pigweed	5.4	9.5	3.7	2.7	28.6	49.2	51.6	52.0	52.0	51.9	52.4
Pumpkin	5.6	8.8	4.3	5.6	30.0	47.1	48.9	49.4	49.6	49.5	50.1
Sorghum	5.0	9.0	4.2	2.1	24.4	46.7	49.1	49.6	49.8	49.9	50.3
Soybean	10.0	15.6	8.7	5.4	32.5	50.0	51.4	51.8	51.9	51.8	52.2
Sugarcane	7.5	12.2	6.9	4.1	26.7	45.0	46.9	47.2	47.3	46.9	47.6
Sunflower	6.3	9.1	5.7	5.1	27.8	46.4	48.4	48.8	48.8	48.4	49.1
Tomato	2.6	5.5	1.5	.9	23.6	41.9	43.8	44.3	44.4	44.0	44.7
Watermelon	5.2	9.6	4.3	2.0	28.7	45.2	46.6	47.1	47.4	47.2	47.9
Wheat	1.9	5.8	2.1	.7	20.3	41.8	43.4	43.9	44.1	43.9	44.6

Crop	Transmittance of light at wavelengths of—									
	1,050 nm.	1,100 nm.	1,150 nm.	1,200 nm.	1,250 nm.	1,300 nm.	1,350 nm.	1,400 nm.	1,450 nm.	1,500 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	46.6	46.3	45.0	45.1	45.6	44.0	39.4	26.1	20.5	25.6
Bean	42.4	41.9	39.9	40.0	40.2	38.1	33.5	17.3	11.8	17.3
Cantaloup	49.5	49.0	46.5	46.6	47.0	44.5	39.2	20.6	14.6	19.7
Corn	51.7	51.6	49.7	49.8	50.5	49.0	45.9	28.8	20.5	26.8
Cotton	49.9	49.6	47.8	47.9	48.3	46.6	42.7	26.7	19.6	25.4
Lettuce	54.9	53.7	48.2	47.4	48.0	43.7	35.9	14.6	6.2	11.1
Okra	47.8	47.6	46.0	46.1	46.5	45.0	41.5	26.8	19.3	24.5
Onion	55.4	54.1	48.2	47.4	48.1	43.4	35.1	12.5	4.1	8.7
Orange	39.5	39.3	37.7	37.6	38.2	36.9	33.7	20.1	13.0	17.2
Peach	48.3	48.1	47.1	47.3	47.7	46.7	43.9	31.5	26.2	31.3
Pepper	47.0	46.7	44.9	45.0	45.4	43.7	39.8	23.9	16.9	22.7
Pigweed	52.9	52.6	51.0	51.2	51.6	49.9	45.8	29.9	23.1	29.1
Pumpkin	50.6	50.4	49.1	49.3	49.7	48.2	43.7	29.5	23.8	29.7
Sorghum	50.8	50.7	49.8	50.0	50.4	49.6	47.3	35.1	28.2	33.2
Soybean	52.6	52.4	51.4	51.6	51.9	50.8	48.0	34.9	28.7	34.3
Sugarcane	48.1	47.9	46.0	46.0	46.5	44.9	40.8	24.6	17.3	23.0
Sunflower	49.7	49.2	46.8	46.8	47.3	45.1	40.0	22.2	15.0	21.0
Tomato	45.3	44.9	42.6	42.6	43.0	40.7	35.9	18.6	12.3	17.9
Watermelon	48.5	48.2	46.3	46.5	47.0	45.0	40.7	24.1	18.3	24.3
Wheat	45.2	45.1	43.4	43.6	44.2	42.8	39.7	24.3	18.5	23.9

TABLE 13.—*Average percent light transmittance of upper leaf surfaces of 10 leaves for each of 20 crops for 41 wavelengths over the 500- to 2,500-nm. wavelength interval*—Continued

Crop	Transmittance of light at wavelengths of—									
	1,550 nm.	1,600 nm.	1,650 nm.	1,700 nm.	1,750 nm.	1,800 nm.	1,850 nm.	1,900 nm.	1,950 nm.	2,000 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	32.0	35.8	37.6	37.0	35.4	34.1	25.1	8.8	6.7	12.3
Bean	24.9	29.6	32.2	32.2	29.5	27.9	18.5	3.7	1.9	5.4
Cantaloup	28.2	33.7	36.6	36.5	33.6	32.0	21.8	4.2	2.1	6.0
Corn	35.1	40.2	43.0	43.1	40.6	39.6	32.0	6.5	5.0	11.8
Cotton	33.2	38.0	40.4	40.3	38.1	37.0	27.1	7.4	4.5	10.2
Lettuce	19.9	26.6	30.5	31.0	27.0	24.4	15.2	2.1	.5	1.7
Okra	32.0	36.6	39.2	39.1	37.0	35.9	27.3	8.6	5.2	10.7
Onion	17.5	24.3	28.4	28.8	24.7	22.0	13.1	1.2	.5	.6
Orange	23.5	27.6	30.0	29.6	27.6	26.9	20.2	5.3	2.6	6.2
Peach	37.4	40.9	42.8	42.3	40.9	40.6	31.7	12.6	10.4	17.3
Pepper	30.4	35.3	37.8	37.8	35.4	34.0	25.0	6.3	3.8	8.9
Pigweed	37.1	41.9	44.5	44.4	42.2	41.0	30.3	9.9	6.9	13.5
Pumpkin	36.8	41.2	43.5	43.1	41.1	39.5	29.2	10.2	8.3	14.9
Sorghum	39.9	44.0	46.2	46.3	44.8	44.1	36.6	15.4	12.2	19.9
Soybean	41.3	45.3	47.4	47.5	45.8	44.8	35.5	14.6	11.7	19.3
Sugarcane	30.7	35.7	38.5	38.4	36.0	34.8	25.1	6.7	4.0	9.3
Sunflower	29.1	34.4	37.0	36.6	34.0	32.7	22.5	6.0	2.3	6.5
Tomato	25.7	30.8	33.4	33.3	30.5	29.1	19.6	3.7	1.8	5.4
Watermelon	31.8	36.5	38.8	38.6	36.2	35.3	25.3	6.1	4.6	10.1
Wheat	30.7	34.7	36.8	36.3	34.3	33.7	26.7	6.0	5.2	10.7

Crop	Transmittance of light at wavelengths of—									
	2,050 nm.	2,100 nm.	2,150 nm.	2,200 nm.	2,250 nm.	2,300 nm.	2,350 nm.	2,400 nm.	2,450 nm.	2,500 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	17.3	21.2	24.0	25.2	23.3	19.8	16.2	12.1	9.8	6.9
Bean	10.3	15.3	18.6	19.7	18.4	15.2	11.3	7.8	4.9	3.5
Cantaloup	11.5	16.9	20.5	21.8	20.1	16.4	12.1	8.1	5.0	3.4
Corn	18.6	24.6	28.5	30.3	28.3	24.4	19.9	14.8	9.7	7.0
Cotton	16.8	22.6	26.2	27.7	26.1	22.5	17.9	12.9	8.8	6.6
Lettuce	4.5	8.8	12.2	13.5	12.2	9.0	5.6	2.9	1.4	.8
Okra	16.8	22.2	25.7	27.1	25.7	22.2	18.1	13.6	9.7	7.5
Onion	2.5	6.0	9.0	10.2	8.8	6.0	3.1	1.2	.5	.5
Orange	10.3	14.1	16.8	18.1	16.5	13.6	10.7	7.8	5.1	3.8
Peach	23.4	28.1	31.2	32.5	30.6	27.2	23.6	19.1	14.7	12.2
Pepper	15.0	20.5	24.2	25.6	24.2	20.8	16.4	11.9	8.1	6.0
Pigweed	20.7	26.8	30.7	32.2	30.6	26.9	22.2	17.0	12.4	9.6
Pumpkin	21.4	26.8	30.1	31.3	29.4	25.8	21.5	16.7	11.9	10.2
Sorghum	26.7	31.9	35.3	36.9	35.4	32.1	28.2	23.6	18.4	15.6
Soybean	26.7	32.7	36.3	37.7	36.3	33.0	28.6	23.5	18.5	15.8
Sugarcane	15.1	20.0	23.7	25.0	23.0	19.3	15.1	10.8	7.0	4.9
Sunflower	11.9	17.1	20.5	21.6	19.7	16.1	12.1	8.2	5.0	3.3
Tomato	10.2	15.2	18.6	19.8	18.2	14.8	10.8	7.2	4.3	3.0
Watermelon	16.1	21.3	24.7	26.1	24.4	20.7	16.6	12.2	8.2	6.3
Wheat	15.9	20.4	23.3	24.7	22.8	19.6	16.2	12.3	8.6	6.5

TABLE 14.—*Average percent light absorptance for upper leaf surfaces of 10 leaves for each of 20 crops for 41 wavelengths over the 500– to 2,500–nm. wavelength interval*

Crop	Absorptance of light at wavelengths of—										
	500 nm.	550 nm.	600 nm.	650 nm.	700 nm.	750 nm.	800 nm.	850 nm.	900 nm.	950 nm.	1,000 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	89.5	87.0	91.8	89.1	48.5	9.6	4.7	4.2	4.3	5.0	4.2
Bean	77.9	70.6	82.4	85.7	36.1	3.4	1.2	1.0	11.5	2.7	1.8
Cantaloup	83.5	73.6	86.0	87.7	43.8	7.6	4.2	3.7	3.9	5.2	3.9
Corn	83.6	74.0	84.3	90.0	52.6	5.7	3.2	2.7	2.7	3.9	3.2
Cotton	82.1	75.1	85.0	88.1	40.8	6.4	3.7	3.4	3.8	4.8	4.0
Lettuce	34.0	25.4	33.8	42.4	16.8	7.1	6.8	7.0	8.5	12.8	11.0
Okra	83.3	72.2	84.7	86.7	43.8	8.2	4.5	4.1	4.1	4.9	4.0
Onion	78.2	69.7	80.7	85.3	39.3	6.2	3.8	4.0	5.4	9.4	7.5
Orange	90.4	87.9	92.3	92.4	53.5	10.8	6.0	5.6	5.7	6.4	5.5
Peach	86.8	82.9	89.1	88.5	43.8	6.8	3.2	2.9	3.0	3.4	2.8
Pepper	80.3	70.6	82.6	87.5	38.8	4.7	2.2	1.9	2.2	3.3	2.4
Pigweed	83.7	78.2	87.0	88.3	44.9	6.9	2.7	2.5	2.6	3.4	2.5
Pumpkin	84.2	79.5	86.8	83.8	40.9	8.0	4.7	4.3	4.2	4.6	3.2
Sorghum	80.1	73.8	82.6	86.6	47.4	7.5	3.6	3.0	2.8	3.3	2.7
Soybean	79.1	71.3	82.7	86.6	38.7	4.4	2.0	1.8	1.8	2.3	1.8
Sugarcane	76.6	69.2	79.7	84.5	43.4	9.2	6.2	6.0	6.3	7.5	6.7
Sunflower	84.1	79.9	85.9	86.4	44.8	8.2	4.3	3.8	4.1	5.1	4.1
Tomato	87.4	83.6	90.0	90.4	50.6	11.5	7.8	7.1	7.1	8.2	7.0
Watermelon	82.9	75.9	85.0	88.1	40.9	9.2	6.5	5.9	5.7	6.5	5.3
Wheat	87.8	80.7	88.3	91.6	52.5	8.0	5.1	4.4	4.4	5.1	4.2

Crop	Absorptance of light at wavelengths of—									
	1,050 nm.	1,100 nm.	1,150 nm.	1,200 nm.	1,250 nm.	1,300 nm.	1,350 nm.	1,400 nm.	1,450 nm.	1,500 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	3.6	4.4	7.9	8.1	7.3	10.8	19.5	47.6	60.4	51.3
Bean	1.0	2.1	6.5	6.5	6.2	11.1	21.6	57.2	69.8	58.1
Cantaloup	2.9	4.0	9.0	9.1	8.5	13.5	24.1	58.8	70.6	61.3
Corn	2.3	2.8	7.0	7.1	6.0	9.3	15.8	47.8	62.7	52.3
Cotton	3.2	4.1	7.9	8.0	7.5	11.4	19.9	51.6	65.1	55.0
Lettuce	8.8	11.3	21.5	23.0	22.2	30.0	42.7	73.6	84.7	78.5
Okra	3.2	4.0	7.4	7.7	7.0	10.5	18.1	47.6	62.6	53.2
Onion	5.2	7.7	18.4	20.0	19.0	27.6	41.9	77.2	89.1	82.9
Orange	4.8	5.3	9.2	9.6	8.8	11.9	19.2	48.6	64.6	56.2
Peach	2.3	2.8	5.2	5.0	4.5	6.8	13.1	38.3	49.5	39.9
Pepper	1.6	2.5	6.5	6.6	6.0	10.0	18.5	51.1	65.4	54.7
Pigweed	2.0	2.7	6.2	6.3	5.8	9.5	18.0	48.6	61.3	51.0
Pumpkin	3.1	4.0	6.8	6.7	6.4	9.8	18.8	45.9	57.2	46.8
Sorghum	2.2	2.5	4.7	4.8	4.2	6.2	11.0	33.9	47.1	38.6
Soybean	1.2	1.8	4.1	4.0	3.7	6.1	11.9	37.4	49.5	39.7
Sugarcane	5.9	6.7	11.1	11.4	10.7	14.6	23.3	54.7	68.2	58.8
Sunflower	3.2	4.3	9.1	9.2	8.6	13.3	23.6	57.3	70.7	60.6
Tomato	6.0	7.0	12.1	12.1	11.5	16.6	26.9	60.9	73.3	63.2
Watermelon	4.4	5.3	9.2	9.2	8.6	12.8	21.8	54.0	65.1	54.5
Wheat	3.3	3.8	7.7	7.6	6.6	10.0	16.8	48.0	59.7	49.6

TABLE 14.—*Average percent light absorption for upper leaf surface of 10 leaves for each of 20 crops for 41 wavelengths over the 500-to 2,500-nm. wavelength interval*—Continued

Crop	Absorptance of light at wavelengths of—									
	1,550 nm.	1,600 nm.	1,650 nm.	1,700 nm.	1,750 nm.	1,800 nm.	1,850 nm.	1,900 nm.	1,950 nm.	2,000 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	39.0	31.7	28.3	29.7	33.4	35.6	51.8	81.5	85.7	77.5
Bean	42.1	32.0	26.9	27.3	33.0	36.8	57.3	88.3	92.1	85.2
Cantaloup	46.3	36.4	31.4	35.0	37.6	40.6	58.8	87.8	91.1	85.4
Corn	37.7	28.8	24.1	24.4	29.4	31.6	44.9	85.6	87.8	78.5
Cotton	40.6	31.7	27.2	27.8	32.5	35.1	52.9	85.0	89.5	82.0
Lettuce	67.1	58.1	52.7	52.2	58.0	61.8	74.2	91.7	93.9	91.9
Okra	39.2	30.4	25.8	26.5	30.7	33.2	49.7	82.1	87.8	79.9
Onion	70.5	60.6	54.4	54.2	60.7	64.9	77.5	93.9	95.1	94.5
Orange	43.2	34.8	30.2	31.4	35.9	17.7	51.9	83.3	88.8	81.8
Peach	28.1	21.6	18.3	19.6	22.6	25.8	40.9	74.9	79.2	68.4
Pepper	39.5	30.1	25.3	25.6	30.8	33.8	51.6	85.1	89.5	81.7
Pigweed	36.8	28.1	23.7	24.3	28.8	31.4	50.1	82.4	87.4	78.6
Pumpkin	33.9	26.1	22.0	23.8	27.6	31.0	49.2	80.8	84.0	74.5
Sorghum	26.9	19.9	16.4	16.8	20.0	21.6	35.1	70.5	75.9	64.5
Soybean	26.9	19.5	15.9	16.2	19.8	21.8	38.9	75.3	80.2	68.6
Sugarcane	45.0	36.0	31.1	31.5	36.5	39.3	55.6	85.7	89.8	82.5
Sunflower	46.0	36.4	31.7	32.9	37.9	40.7	58.6	87.1	91.2	85.4
Tomato	48.7	39.2	34.5	35.1	40.6	43.6	61.3	89.0	92.2	86.7
Watermelon	40.8	32.3	28.2	29.1	33.9	36.0	54.2	85.9	88.5	80.8
Wheat	36.7	29.0	25.1	26.3	30.6	32.0	45.8	84.2	85.8	76.5

Crop	Absorptance of light at wavelengths of—									
	2,050 nm.	2,100 nm.	2,150 nm.	2,200 nm.	2,250 nm.	2,300 nm.	2,350 nm.	2,400 nm.	2,450 nm.	2,500 nm.
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Avocado	69.4	63.1	57.9	55.4	59.3	66.0	72.2	78.4	82.3	86.1
Bean	75.5	65.7	58.8	56.3	60.1	67.6	75.9	82.8	89.0	90.6
Cantaloup	77.4	68.9	63.0	60.7	64.2	71.0	78.0	83.9	88.4	90.6
Corn	68.8	59.6	53.2	50.0	54.1	61.2	68.6	75.9	82.8	86.3
Cotton	72.4	63.3	57.1	63.3	42.0	65.0	72.3	79.6	85.2	88.1
Lettuce	88.1	82.9	78.6	77.1	79.1	83.3	87.8	91.3	93.4	94.3
Okra	70.4	61.5	55.3	52.6	56.0	62.8	70.1	77.2	83.0	86.0
Onion	91.9	87.4	83.3	81.8	83.8	87.7	91.5	94.1	94.9	95.0
Orange	73.9	66.8	61.0	58.3	62.3	69.0	75.2	81.2	85.9	88.4
Peach	58.3	50.3	44.5	41.9	46.4	53.5	60.4	67.8	74.6	78.3
Pepper	71.8	62.4	55.6	52.9	56.5	63.8	71.8	79.2	85.0	88.2
Pigweed	68.3	58.9	52.5	50.1	53.5	60.2	67.9	75.4	81.7	85.3
Pumpkin	64.5	56.0	50.4	47.9	52.4	59.3	66.4	73.6	80.5	82.7
Sorghum	54.2	46.0	40.2	37.4	41.0	47.5	54.4	61.8	69.2	73.2
Soybean	56.7	46.7	40.2	37.6	41.0	47.9	56.0	64.4	72.0	76.1
Sugarcane	74.3	66.9	60.8	58.6	62.3	68.9	75.4	81.4	86.5	89.1
Sunflower	77.6	69.7	64.1	62.2	65.9	72.3	78.6	83.6	88.5	90.7
Tomato	79.1	71.1	65.2	63.0	66.4	73.0	79.7	85.4	89.6	91.6
Watermelon	71.8	63.4	57.6	55.1	58.9	65.8	72.6	79.3	84.9	87.5
Wheat	67.5	59.4	54.1	50.9	55.5	62.8	68.8	75.5	81.7	85.0

Glossary of terms

References by Esau (*8*), Fahn (*9*), and Fuller and Tippo (*11*) were used for the definitions below.

Abaxial — Directed outwards from the axis (leaf surface faces away from the stem).

Adaxial — Directed toward the axis (leaf surface faces toward the stem).

Bulliform cell — An enlarged epidermal cell occurring in longitudinal rows of similar cells in the *Gramineae*. It is thought to play a role in the rolling and unrolling of leaves.

Chlorenchyma — Chloroplast-containing parenchyma tissue.

Compact leaf — Leaf, as corn (*Zea mays* L.), with a mesophyll comprised of relatively compact chlorenchyma with few intercellular spaces (nonporous mesophyll).

Cuticle — A layer of fatty substance, cutin, on the epidermal outer cell walls, which is almost impermeable to water.

Dorsiventral leaf — A leaf with palisade parenchyma cells on one side of the blade and spongy parenchyma cells on the other.

Druse — A globular compound crystal that has many component crystals projecting from its surface.

Epidermis — The outer cellular layer of a leaf, primary in origin; if multiseriate (multiple layers of epidermis), only the outer layer differentiates epidermal characteristics.

Genus (pl. genera) — A group of closely related species. In the binomial system of nomenclature, the generic name usually refers to some distinctive character of a plant and the species name is descriptive of a plant.

	Related species constitute a genus, and related genera constitute a family.
Intercellular space	Space among cells within the leaf.
Isolateral leaf	A leaf that has palisade parenchyma cells on both sides of the blade.
Lacuna (pl. lacunae)	Air space.
Lysigenous space	An intercellular space that originated by cell-wall dissolutions.
Mesophyll	Parenchyma tissue of a leaf between the epidermal layers.
Multiseriate	Consisting of many layers of cells.
Nectary	A multicellular glandular structure in leaves that secretes a sugary liquid.
Palisade parenchyma layer	Parenchyma layer of a leaf mesophyll whose cells have an elongated form (palisade cells) perpendicular to the leaf surface.
Paradermal (tangential)	Refers to a section made parallel with the surface of a leaf.
Parenchyma cell	Thin-walled cell found in leaves that is capable of growth and division.
Pubescent	Covered with hairs.
Schlerenchyma	Thick-walled cells whose principal function is strengthening plant parts. Schlerenchyma cells may or may not have a protoplast at maturity.
Spongy parenchyma layer	Parenchyma layer of a leaf mesophyll with conspicuous intercellular spaces (porous mesophyll).
Storage cells	Large thin-walled cells used for storage of water and mucilages.
Succulent leaf	Fleshy-type leaves (malacophyllous) with many cells that store water and mucilages.
Transection	See transverse.
Transverse	A cross section. A section taken perpendicular to the longitudinal axis of the cell. Also called transection.

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