Additional Appendix F (not in printed book)

Specific absorption coefficients for major algal chlorophylls, bacteriochlorophylls and carotenoids

EINAR SKARSTAD EGELAND

F.1 Introduction

This appendix lists all the absorption coefficients for algal chlorophylls and carotenoids found in the literature available to the author, illustrating the variation between published values, and providing coefficients for other solvents than the ones given in the data sheets section. For the quantification of phytoplankton pigments, the most accurate absorption coefficients should be used. From the available values, the one found to be most trustworthy has been included in the pigments data sheets (see Part VII, print version of this volume and this website).

F.2 Determination and use of absorption coefficients

To determine specific absorption coefficients, pigments of the very highest purity (preferably checked by NMR) must be obtained in amounts sufficient to weigh them, then dissolve them in a pure solvent and determine their absorption in a calibrated spectrophotometer. Some scientists have used an alternative to the weighing procedure by determining the magnesium content in the case of chlorophyll pigments, using atomic absorption spectrometry (Porra *et al*., 1989; Araujo *et al*., 1995).

Once the specific absorption coefficient for a given pigment in a selected solvent is known, the concentrations of other solutions of the same compound can be determined from spectrophotometric readings at appropriate wavelengths (generally at one of the peaks of absorbance: Soret (blue) or red peak for chlorophylls, band II for carotenoids – see Jeffrey *et al.*, 1997). A calibrated spectrophotometer must be used, and solution(s) of the pure pigment must be prepared using pure solvents and calibrated pipettes (calibrated for the solvent used, note that several plastics are not compatible with some solvents) or volumetric flasks. Absorbance values are determined relative to a zero value where pigments absorb no light (commonly 750 nm). The unknown concentration can then be determined from the following formula (see also Appendix 5A):

> Pigment concentration c [g L^{-1}] = (absorbance A at chosen peak wavelength λ – absorbance at 750 nm) / (specific absorption coefficient d at chosen peak wavelength [L g^{-1} cm^{-1}] • absorption path length b [cm])

Note that absorbance (A, optical density) values are dimensionless, and that the maximum absorbance should be used, even when the peak is slightly shifted from the maximum wavelength found in the literature.

When working with phytoplankton pigments, only small amounts of pure pigments are generally available and only a few pigments have been purified and prepared in sufficient amount to determine specific absorption coefficients. Hence coefficients are available only for a small number

of pigments, and only in a few solvents, leading to limitations that must be recognized and are dealt with in the next sections.

F.3 Uncertainties in the given values

It is essential to use an accurate specific absorption coefficient for a selected pigment in a selected solvent; otherwise the amount of pigment calculated could easily be ± 20% of the true value.

Regrettably, due to the meticulous accuracy required to prepare a pure, solid pigment in the mg range (Jeffrey, 1997; Repeta and Bjørnland, 1997), absorption coefficients are not measured regularly. For some pigments they have never been measured at all.

All measured values have their own uncertainty and due to difficulties in preparing a pure, dry, solid pigment free of any forms of impurities (including lipids, solvents and pigment derivatives), absorption coefficients should only ever be given to three significant figures. Precision is probably overestimated since several (sometimes quite different) specific absorption coefficient values are available in the scientific literature for the same solvent – this is more apparent for the most common pigments. In general, when more than one value for a pigment in a certain solvent is available, the highest value is recommended.

F.4 Conversion of absorption coefficients units

In this chapter and in the data sheets, all absorption coefficients have been given as specific absorption coefficients, d (L g^{-1} cm^{-1}). For carotenoids, the absorption coefficient (also denoted extinction coefficient) has traditionally been given as $E^{1\%}_{1\,cm}$ (100 mL g^{-1} cm^{-1}, also denoted $A^{1\%}_{1\,cm}$). To convert from the given d to $E^{1\%}_{1\,cm}$, the d value is multiplied by a factor of 10.

In some literature, the absorption coefficient is given as the molar absorption coefficient, ε (L mol^{-1} cm^{-1}), which is sometimes also given as the $\log_{10}\varepsilon$ value. To convert from the given d to ε value, multiply d with the pigment's molecular weight.

F.5 Use of other solvents

Specific absorption coefficients are valid only for the solvent they have been determined for. A pigment standard used for calibration of an HPLC instrument must be dissolved in the appropriate solvent for the absorption coefficient used. If it cannot be injected into the HPLC due to solvent incompatibility, a change of solvent is required. The easiest way is to find a d value for the preferred solvent. However, if these values have never been published, the pigment must be dissolved in the solvent that was used to determine the d value. To obtain a pigment solution that can be injected in the HPLC after determining the absorption of the pigment solution used for calibration, the solvent must be evaporated in the dark under a gentle stream of nitrogen or argon, and an HPLC compatible solvent must then be added. To avoid solubility problems, the first solvent should not be fully evaporated, but only to about 5% of the initial volume. If split peaks are observed in the HPLC chromatograms this may be caused by solvent incompatibility and the initial volume must therefore be further reduced before adding the HPLC compatible solvent.

Furthermore, one should also look carefully for any sign of precipitation of the pigment in the new solvent, as this would be critically detrimental to the calibration of the HPLC system.

F.6 Table of specific absorption coefficient values

All reported absorption coefficients are given in Table F.1 below. The value considered to be of greatest quality according to the author of this Appendix is given in the data sheets (Part VII, this volume, and this website) and shown in bold in the following Table. Values in italics are recommendations for other solvents.

Table F.1. Specific absorption coefficients for major algal chlorophylls, bacteriochlorophylls and carotenoids in various solvents.

Values in bold are the author's recommendation for the selected pigment. Values in italics are the author's recommendation for the selected pigment in other solvents. Where wavelength is not given, use the wavelength for the peak maximum.

Name	***d*** **(L g^{-1} cm^{-1})**	**λ_{max} (nm)**	**Solvent**	**Reference**	**Remarks**
Alloxanthin	**216**	464	benzene	Davies *et al.* (1984)	3*R*,3'*R*
	232	462	benzene	Davies *et al.* (1984)	3*RS*,3'*RS*
Antheraxanthin	**235**	446	ethanol	Hager and Meyer-Bertenrath (1966)	
	237	445	diethyl ether:methylbutane:ethanol 5:5:2	Märki-Fischer *et al.* (1982)	
Astaxanthin	189	489	benzene	Buchwald and Jencks (1968)	
	209	488	chloroform	Englert *et al.* (1977)	
	209	489	chloroform	Englert *et al.* (1977)	
	190	492	chloroform	Widmer *et al.* (1981a)	

	204	492	chloroform	Widmer *et al.* (1981a)	
	192	492	chloroform	Widmer *et al.* (1981b)	
	202	492	chloroform	Widmer *et al.* (1981b)	
	181	not given	ethanol	G. Wald, unpubl., see Buchwald and Jencks (1968)	Use peak absorption
	208	472	hexane	Buchwald and Jencks (1968)	
	237	470	hexane	Karrer and Würgler (1943)	Value taken from figure
	213	not given	hexane	G. Wald, unpubl., see Buchwald and Jencks (1968)	Use peak absorption
	206	473	methanol	Buchwald and Jencks (1968)	
	188	492	pyridine	Buchwald and Jencks (1968)	
	188–*193*	not given	pyridine	Kuhn *et al.* (1939)	Several absorption coefficient measurements; use peak absorption
	164	not given	pyridine	G. Wald, unpubl., see Buchwald and Jencks (1968)	Use peak absorption
Auroxanthin	185	402	ethanol	Davies (1965)	

	181	403	ethanol	Karrer and Rutschmann (1942)	Value taken from figure
Bacteriochlorophyll *a*	78.4	770	acetone	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	76.0	771	acetone	Permentier *et al.* (2000)	
	75.9	770	acetone	Sauer *et al.* (1966)	
	66.9	769	acetonitrile	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	94.8	783	benzene	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	99.6	782	benzene	Permentier *et al.* (2000)	
	85.1	780	chloroform	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	82.1	774	dichloromethane	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	111	771	diethyl ether	Connolly *et al.* (1982)	
	99.8	771	diethyl ether	Hartwich *et al.* (1998)	
	102	769–770	diethyl ether	Holt and Jacobs (1954)	
	106	771	diethyl ether	Permentier *et al.* (2000)	
	105	770	diethyl ether	Sauer *et al.* (1966)	

	100	773	diethyl ether	Smith and Benitez (1955)	
	102	770	diethyl ether	Strain and Svec (1966)	
	105	772	diethyl ether	Weigl (1953)	
	126	772	dioxane	Clayton (1966)	Based on the *d* value for diethyl ether (Weigl, 1953)
	68.9	774	ethanol	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	65.4	774	ethanol	Permentier *et al.* (2000)	
	68.0	773	ethanol	Sauer *et al.* (1966)	
	66.0	775	methanol	Cohen-Bazire and Sistrom (1966)	
	64.9	772	methanol	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	60.1	771	methanol	Permentier *et al.* (2000)	
	46.1	772	methanol	Smith and Benitez (1955)	
	70.4	776	propan-1-ol (= 1-propanol)	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	71.9	776	propan-2-ol (= 2-propanol)	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	71.4	777	propan-2-ol (= 2-propanol)	Permentier *et al.* (2000)	

	98.2	782	pyridine	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	83.4	781	pyridine	Hartwich *et al.* (1998)	
	97.0	781	tetrachloromethane	Clayton (1966)	Based on the *d* value for diethyl ether (Weigl, 1953)
	113	781	tetrachloromethane	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	96.5	780	tetrachloromethane	Sauer *et al.* (1966)	Monomer
	59.2	785	tetrachloromethane	Sauer *et al.* (1966)	Dimer; per molecule of Chl *a*
	112	771	tetrahydrofuran	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
	101	781	toluene	Connolly *et al.* (1982)	Based on the *d* value for diethyl ether
Canthaxanthin	209	480	benzene	Warren and Weedon (1958)	
	198	480	benzene	Petracek and Zechmeister (1956b)	
	209	480	benzene	Petracek and Zechmeister (1956b)	
	220	469	cyclohexane	Surmatis *et al.* (1970)	
	197	468	hexane	Entschel and Karrer (1958)	

	202	466	hexane	Petracek and Zechmeister (1956a)	
	220	465–467	petroleum ether	Zeller *et al.* (1959)	
β,β-Carotene	250	454	acetone	Hiyama *et al.* (1969)	
	234	465	benzene	Isler *et al.* (1956*b*)	
	201	484	carbon disulphide	Isler *et al.* (1956*b*)	
	194	483	carbon disulphide	Mackinney (1935)	
	195	480	carbon disulphide	Smith (1936)	Value taken from figure
	220	463	chloroform	Gillam (1935)	
	240	465	chloroform	Isler *et al.* (1956*b*)	
	252	456	cyclohexane	Chechak *et al.* (1964)	
	251	457	cyclohexane	Isler *et al.* (1956*b*)	
	251	457	cyclohexane	Isler and Schudel (1963)	
	245	456	cyclohexane	Nürrenbach and Pommer (1969)	

	250	456	cyclohexane	Surmatis *et al.* (1969)	
	245	463	dichloromethane	Isler *et al.* (1956*b*)	
	247	461	dioxane	Isler *et al.* (1956*b*)	
	262	453	ethanol	Isler *et al.* (1956*b*)	
	256	451	hexane	Cholnoky *et al.* (1967)	
	259	453	hexane	Isler *et al.* (1956*b*)	
	258	450	hexane	Zscheile *et al.* (1942)	
	251	451	isooctane	Bickoff *et al.* (1948)	
	250	450	methylcyclohexane	Kabbe *et al.* (1965)	
	294	452–3	petroleum ether	Inhoffen *et al.* (1950a)	
	291	452–3	petroleum ether	Inhoffen *et al.* (1950b)	
	256	452–3	petroleum ether	Isler *et al.* (1956*b*)	
	255	452–3	petroleum ether	Isler *et al.* (1956*d*)	
β,ε-Carotene	270	448	acetone	Hiyama *et al.* (1969)	
	242	456	chloroform	Hager and Meyer-Bertenrath	

				(1966)	
	270	445	hexane	Bush and Zechmeister (1958)	
	272	446	hexane	Cholnoky *et al.* (1967)	
	270	446	hexane	Eugster and Karrer (1955)	Regrettably wrong reference on the data sheet (should be [56], not [57])
	266	445	hexane	Tscharner *et al.* (1957)	
	272	445	hexane	Zcheile *et al.* (1942)	
	267	446	isooctane	Bickoff *et al.* (1948)	
	264	447	petroleum ether	Inhoffen *et al.* (1954)	
	259	447	petroleum ether	Inhoffen *et al.* (1954)	
	254	447	petroleum ether	Inhoffen *et al.* (1954)	
	280	444	petroleum ether	Rüegg *et al.* (1961)	
	279	446	petroleum ether	Rüegg *et al.* (1961)	
β,ψ-Carotene	**272**	462	hexane	Zechmeister *et al.* (1943)	Regrettably incorrect *d* value (276) on the data sheet
	310	462	petroleum ether	Rüegg *et al.* (1961)	

	319	459	petroleum ether	Manchard *et al.* (1965)	
	201	497	carbon disulphide	Mackinney (1935)	
ε,ε-Carotene	300	441	petroleum ether	Manchard *et al.* (1965)	
	312	440	petroleum ether	Schwieter *et al.* (1965)	
ψ,ψ-Carotene (= Lycopene)	253	508	carbon disulphide	Mackinney (1935)	
	200	480	chloroform	Gillam (1935)	
	347	473	hexane	Zechmeister *et al.* (1943)	
	335	476	methylcyclohexane	Kabbe *et al.* (1965)	
	345	472	petroleum ether	Isler *et al.* (1956*a*)	
Chlorophyll *a*	88.2	663	acetone	Jeffrey and Humphrey (1975)	Value recommended in Jeffrey *et al*. (1997)
	112	430	acetone	Lichtenthaler (1987)	
	92.5	662	acetone	Lichtenthaler (1987)	
	61.3	662	acetone	Trurnit and Colmano (1959)	
	92.6	663	acetone	Vernon (1960)	

	91.0	662	acetone	Watanabe *et al.* (1984)	
	91.8	662	acetone	Wintermans and Mots (1965)	
	91.5	662	acetone	Ziegler and Egle (1965)	
	87.7	664	90% acetone	Jeffrey and Humphrey (1975)	Value recommended in Jeffrey *et al.* (1997)
	89.0	665	90% acetone	Parsons and Strickland (1963)	
	91.1	664	90% acetone	Vernon (1960)	
	89.7	663	90% acetone	Ziegler and Egle (1965)	
	95.8	431	80% acetone	Lichtenthaler (1987)	
	86.3	663	80% acetone	Lichtenthaler (1987)	
	90.8	430	80% acetone	Mackinney (1941)	
	82.0	663	80% acetone	Mackinney (1941)	
	102	433	80% acetone	Vernon (1960)	
	90.8	665	80% acetone	Vernon (1960)	
	89.5	664	80% acetone	Wintermans and Mots (1965)	

	89.0	664	80% acetone	Ziegler and Egle (1965)	
	86.0	664	buffered 80% acetone	Porra *et al.* (1989)	80% aqueous acetone containing 2.5 mM sodium phosphate buffer, pH 7.8
	88.7	664	75% acetone	Ziegler and Egle (1965)	
	61.2	665	benzene	Trurnit and Colmano (1959)	
	66.0	666	benzene	Trurnit and Colmano (1959)	
	89.2	665	benzene	Watanabe *et al.* (1984)	
	90.4	666	chloroform	Wellburn (1994)	High resolution spectrophotometer
	94.6	666	chloroform	Wellburn (1994)	Low resolution spectrophotometer
	160	431	diethyl ether	Hagenbach *et al.* (1936)	
	80.9	656	diethyl ether	Hagenbach *et al.* (1936)	
	108	430	anhydrous diethyl ether	Heierle (1935)	
	91.0	662	anhydrous diethyl ether	Heierle (1935)	
	129	428	diethyl ether	Hynninen and Lötjönen (1983)	
	101	660	diethyl ether	Hynninen and Lötjönen (1983)	

	98.1	661	diethyl ether	Jeffrey and Humphrey (1975)	
	130	428	anhydrous diethyl ether	Lichtenthaler (1987)	
	102	660	anhydrous diethyl ether	Lichtenthaler (1987)	
	96.6	661	diethyl ether	Pennington *et al.* (1964)	
	132	430	diethyl ether	Smith and Benitez (1955)	
	101	662	diethyl ether	Smith and Benitez (1955)	
	125	429	diethyl ether	Strain *et al.* (1963)	
	96.6	661	diethyl ether	Strain *et al.* (1963)	
	70.4	661	diethyl ether	Trurnit and Colmano (1959)	
	74.0	661	diethyl ether	Trurnit and Colmano (1959)	
	101	660	diethyl ether	Watanabe *et al.* (1984)	
	131–138	429	diethyl ether	Zscheile and Comar (1941)	Several absorption coefficient measurements
	100–104	660	diethyl ether	Zscheile and Comar (1941)	Several absorption coefficient measurements
	124	430	5% tetrachloromethane in	Sauer *et al.* (1966)	

			diethyl ether		
	97.1	668	5% tetrachloromethane in diethyl ether	Sauer *et al.* (1966)	
	88.7	664	*N,N*-dimethylformamide	Porra *et al*. (1989)	
	89.8	664	*N,N*-dimethylformamide	Wellburn (1994)	High resolution spectrophotometer
	90.4	664	*N,N*-dimethylformamide	Wellburn (1994)	Low resolution spectrophotometer
	86.7	665	dimethylsulphoxide	Wellburn (1994)	High resolution spectrophotometer
	88.1	665	dimethylsulphoxide	Wellburn (1994)	Low resolution spectrophotometer
	84.5	416	anhydrous ethanol	Heierle (1935)	
	81.1	665	anhydrous ethanol	Heierle (1935)	
	83.9	432	95% ethanol	Lichtenthaler (1987)	
	84.6	664	95% ethanol	Lichtenthaler (1987)	
	83.2	432	96% ethanol	Wintermans and Mots (1965)	
	83.4	665	96% ethanol	Wintermans and Mots (1965)	
	75.0	665	methanol	Lenz and Zeitzschel (1968)	

	77.1	432	methanol	Lichtenthaler (1987)	
	79.2	665	methanol	Lichtenthaler (1987)	
	80.0	665	methanol	Porra *et al.* (1989)	
	76.0	432	90% methanol	Lichtenthaler (1987)	
	79.0	665	90% methanol	Lichtenthaler (1987)	
	76.3	664	85% methanol with dithionite	Porra (1990)	
	63.2	663	10% benzene in Nujol	Trurnit and Colmano (1959)	Nujol is a paraffin oil
	66.4	663	1% pyridine in petroleum ether	Trurnit and Colmano (1959)	
	57.9	665	tetrachloromethane	Trurnit and Colmano (1959)	
	116	433	tetrachloromethane	Sauer *et al.* (1966)	Monomer
	95.0	665	tetrachloromethane	Sauer *et al.* (1966)	Monomer
	93.7	434	tetrachloromethane	Sauer *et al.* (1966)	Dimer; per molecule of Chl *a*
	66.6	668	tetrachloromethane	Sauer *et al.* (1966)	Dimer; per molecule of Chl *a*
	86.6	664	tetrahydrofuran	Hynninen and Sievers (1981)	Assumed to be Chl *a* • H_2O; abs. coeff. value per molecule of Chl *a*

	116	436	tetrahydrofuran	Hynninen and Sievers (1981)	Assumed to be Chl *a* • H_2O; abs. coeff. value per molecule of Chl *a*
	137	435	tetrahydrofuran	Hynninen (1981)	Chl *a* • H_2O; abs. coeff. value per molecule of Chl *a*
	102	664	tetrahydrofuran	Hynninen (1981)	Chl *a* • H_2O; abs. coeff. value per molecule of Chl *a*
Chlorophyll *a*′	**120**	429	diethyl ether	Hynninen and Lötjönen (1983)	
	96.4	661	diethyl ether	Hynninen and Lötjönen (1983)	
	128	436	tetrahydrofuran	Hynninen and Sievers (1981)	Assumed to be Chl *a*′ • H_2O; abs.coeff. value per molecule of Chl *a*′
	96.7	665	tetrahydrofuran	Hynninen and Sievers (1981)	Assumed to be Chl *a*′ • H_2O; abs.coeff. value per molecule of Chl *a*′
Chlorophyll *b*	145	456	acetone	Lichtenthaler (1987)	
	51.7	645	acetone	Lichtenthaler (1987)	
	53.5	647	acetone	Vernon (1960)	
	52.5	645	acetone	Watanabe *et al.* (1984)	

	54.3	645	acetone	Ziegler and Egle (1965)	
	51.4	647	90% acetone	Jeffrey and Humphrey (1975)	Value recommended in Jeffrey *et al.* (1997)
	54.0	645	90% acetone	Parsons and Strickland (1963)	
	52.5	648	90% acetone	Vernon (1960)	
	53.1	646	90% acetone	Ziegler and Egle (1965)	
	135	459	80% acetone	Lichtenthaler (1987)	
	49.2	647	80% acetone	Lichtenthaler (1987)	
	148	460	80% acetone	Vernon (1960)	
	52.5	648–9	80% acetone	Vernon (1960)	
	52.3	647	80% acetone	Ziegler and Egle (1965)	
	51.8	647	buffered 80% acetone	Porra *et al.* (1989)	80% aqueous acetone containing 2.5 mM sodium phosphate buffer, pH 7.8
	52.1	647	75% acetone	Ziegler and Egle (1965)	
	61.9	646	benzene	Watanabe *et al.* (1984)	
	47.5	647	chloroform	Wellburn (1994)	High resolution spectrophotometer

	63.0	648	chloroform	Wellburn (1994)	Low resolution spectrophotometer
	231	450	diethyl ether	Hagenbach *et al.* (1936)	
	79.2	638	diethyl ether	Hagenbach *et al.* (1936)	
	114	454	anhydrous diethyl ether	Heierle (1935)	
	55.7	644	anhydrous diethyl ether	Heierle (1935)	
	176	453	diethyl ether	Hynninen and Lötjönen (1983)	
	63.7	642	diethyl ether	Hynninen and Lötjönen (1983)	
	62.0	643	diethyl ether	Jeffrey and Humphrey (1975)	
	171	452	anhydrous diethyl ether	Lichtenthaler (1987)	
	62.3	642	anhydrous diethyl ether	Lichtenthaler (1987)	
	175	455	diethyl ether	Smith and Benitez (1955)	
	62.0	644	diethyl ether	Smith and Benitez (1955)	
	175	453	diethyl ether	Strain *et al.* (1963)	
	61.8	642	diethyl ether	Strain *et al.* (1963)	
	62.5	642	diethyl ether	Watanabe *et al.* (1984)	

	169–173	453	diethyl ether	Zscheile and Comar (1941)	Several absorption coefficient measurements
	55.4–57.6	643	diethyl ether	Zscheile and Comar (1941)	Several absorption coefficient measurements
	178	452	0.1% tetrachloromethane in diethyl ether	Sauer *et al.* (1966)	
	63.7	642	0.1% tetrachloromethane in diethyl ether	Sauer *et al.* (1966)	
	51.2	647	*N,N*-dimethylformamide	Porra *et al.* (1989)	
	48.1	647	*N,N*-dimethylformamide	Wellburn (1994)	High resolution spectrophotometer
	50.6	647	*N,N*-dimethylformamide	Wellburn (1994)	Low resolution spectrophotometer
	43.2	649	dimethylsulphoxide	Wellburn (1994)	High resolution spectrophotometer
	48.8	649	dimethylsulphoxide	Wellburn (1994)	Low resolution spectrophotometer
	96.4	464	anhydrous ethanol	Heierle (1935)	
	39.8	652	anhydrous ethanol	Heierle (1935)	
	107	464	95% ethanol	Lichtenthaler (1987)	

	41.2	649	95% ethanol	Lichtenthaler (1987)	
	105	469	methanol	Lichtenthaler (1987)	
	38.9	652	methanol	Lichtenthaler (1987)	
	42.5	652	methanol	Porra *et al.* (1989)	
	99.5	469	90% methanol	Lichtenthaler (1987)	
	36.0	652	90% methanol	Lichtenthaler (1987)	
	173	456	tetrachloromethane	Sauer *et al.* (1966)	Monomer
	65.2	645	tetrachloromethane	Sauer *et al.* (1966)	Monomer
	120	464	tetrachloromethane	Sauer *et al.* (1966)	Dimer
	50.2	648	tetrachloromethane	Sauer *et al.* (1966)	Dimer
	171	453	tetrahydrofuran	Hynninen (1981)	Chl *b* • H_2O; abs. coeff. value per molecule of Chl *b*
	61.7	643	tetrahydrofuran	Hynninen (1981)	Chl *b* • H_2O; abs. coeff. value per molecule of Chl *b*
Chlorophyll *b*′	**171**	453	diethyl ether	Hynninen and Lötjönen (1983)	
	61.2	642	diethyl ether	Hynninen and Lötjönen (1983)	

Chlorophyll c_1	348	446	1% pyridine in acetone	Jeffrey (1972)	
	28.6	578	1% pyridine in acetone	Jeffrey (1972)	
	39.2	629	1% pyridine in acetone	Jeffrey (1972)	
	318	443	1% pyridine in 90% acetone	Jeffrey (1972)	
	26.0	579	1% pyridine in 90% acetone	Jeffrey (1972)	
	44.8	631	1% pyridine in 90% acetone	Jeffrey (1972)	
	139	451	methanol	Saitoh *et al.* (1993)	
	8.02	588	methanol	Saitoh *et al.* (1993)	
	14.1	631	methanol	Saitoh *et al.* (1993)	
	154	445	1% pyridine in methanol	Saitoh *et al.* (1993)	
	12.4	584	1% pyridine in methanol	Saitoh *et al.* (1993)	
	21.2	634	1% pyridine in methanol	Saitoh *et al.* (1993)	
	346	462	pyridine	Jeffrey (1972)	
	30.4	593	pyridine	Jeffrey (1972)	
	35.0	640	pyridine	Jeffrey (1972)	

	384	band III	1% pyridine in tetrahydrofuran	Jeffrey (1972)	Wavelength not given
	32.1	band II	1% pyridine in tetrahydrofuran	Jeffrey (1972)	Wavelength not given
	36.1	band I	1% pyridine in tetrahydrofuran	Jeffrey (1972)	Wavelength not given
Chlorophyll c_2	321	445	1% pyridine in acetone	Jeffrey (1972)	
	35.7	581	1% pyridine in acetone	Jeffrey (1972)	
	37.2	630	1% pyridine in acetone	Jeffrey (1972)	
	374	444	1% pyridine in 90% acetone	Jeffrey (1972)	
	30.7	581	1% pyridine in 90% acetone	Jeffrey (1972)	
	40.4	631	1% pyridine in 90% acetone	Jeffrey (1972)	
	95.2	454	methanol	Saitoh *et al.* (1993)	
	9.52	588	methanol	Saitoh *et al.* (1993)	
	10.0	635	methanol	Saitoh *et al.* (1993)	
	122	452	1% pyridine in methanol	Saitoh *et al.* (1993)	
	10.8	587	1% pyridine in methanol	Saitoh *et al.* (1993)	

	13.0	635	1% pyridine in methanol	Saitoh *et al.* (1993)	
	459	466	pyridine	Jeffrey (1972)	
	42.0	597	pyridine	Jeffrey (1972)	
	31.8	642	pyridine	Jeffrey (1972)	
	488	band III	1% pyridine in tetrahydrofuran	Jeffrey (1972)	Wavelength not given
	45.2	band II	1% pyridine in tetrahydrofuran	Jeffrey (1972)	Wavelength not given
	33.2	band I	1% pyridine in tetrahydrofuran	Jeffrey (1972)	Wavelength not given
Chlorophyll *d*	**118**	687	diethyl ether	Holt and Morley (1959)	
	110	688	diethyl ether	Smith and Benitez (1955)	
	97.8	447	diethyl ether	Smith and Benitez (1955)	
Cryptoxanthin	242	465	benzene	Zechmeister and Lemmon (1944)	Value taken from figure
	247	453	ethanol	Strain (1938)	Value taken from figure
	241	449	hexane	Loeber *et al.* (1971)	

	246	452	hexane	Zscheile *et al.* (1942)	Regrettably wrong reference on the data sheet (should be [182], not [180])
	237	452	petroleum ether	Isler *et al.* (1957*a*)	
Diadinoxanthin	**224**	448	acetone	Johansen *et al.* (1974)	The average of the two values given in the article (223, 225), one probably a misprint of the other
	211	446	hexane and petroleum ether	Johansen *et al.* (1974)	
	225	445	methanol	Johansen *et al.* (1974)	
Diatoxanthin	272	453	acetone	Haugan and Liaaen-Jensen (1994)	
Divinylchlorophyll *a*	107	438	80% acetone	Shedbalkar and Rebeiz (1992)	Values not known to the author at the time of data sheets compilation. NMR spectrum shows substantial amounts of impurities.
	77.7	664	80% acetone	Shedbalkar and Rebeiz (1992)	
	124	435	diethyl ether	Shedbalkar and Rebeiz (1992)	
	87.9	660	diethyl ether	Shedbalkar and Rebeiz (1992)	
Divinylchlorophyll *b*	97.0	468	80% acetone	Shedbalkar and Rebeiz (1992)	Values not known to the author at the time of data sheets compilation.
	39.5	651	80% acetone	Shedbalkar and Rebeiz (1992)	

	131	462	diethyl ether	Shedbalkar and Rebeiz (1992)	NMR spectrum shows substantial amounts of impurities.
	48.5	643	diethyl ether	Shedbalkar and Rebeiz (1992)	
Echinenone	209	472	benzene	Warren and Weedon (1958)	
	211	461	cyclohexane	Surmatis *et al.* (1970)	
	214	458	hexane	Petracek and Zechmeister (1956a)	
	216	458	hexane	Ganguly *et al.* (1956)	
	214	456	petroleum ether	Akhtar and Weedon (1959)	
	216	458	petroleum ether	Davies (1965)	
Fucoxanthin	**166**	443	acetone	Haugan and Liaaen-Jensen (1989)	
	160	not given	acetone	Jensen (1966)	Use peak absorption
	106	449	90% acetone	Garside and Riley (1968)	
	203	478	carbon disulphide	Bonnett *et al.* (1969)	
	145	458	chloroform	Gillam (1935)	

	114	450	ethanol	Antia (1965)	
	165	not given	hexane	Jensen (1966)	Use peak absorption
	164–166	not given	petroleum ether	Jensen (1966)	Several absorption coefficient measurements; use peak absorption
Lutein	223	458	benzene	Cholnoky *et al.* (1967)	
	182	474	carbon disulphide	Strain (1938)	
	196	474	carbon disulphide	Strain (1938)	
	237	456	chloroform	Strain (1938)	Value taken from figure
	180	453	chloroform	Gillam (1935)	
	180	456	chloroform	Gillam (1935)	
	237	448	diethyl ether	Bernegg *et al.* (1935)	Value taken from figure
	269	447	anhydrous diethyl ether	Heierle (1935)	
	248	445	diethyl ether	Kar (1937)	
	263	444	diethyl ether	Strain (1938)	Value taken from figure
	267	453	dioxane	Buchecker *et al.* (1974)	

	252	453	dioxane	Mayer and Rüttimann (1980)	
	245	455	dioxane	Strain (1938)	Value taken from figure
	254	447	ethanol	Strain (1938)	Value taken from figure
	255	447	ethanol	Zscheile *et al.* (1942)	
	256	447	ethanol	Zscheile *et al.* (1942)	
	198	443	methanol	Bernegg *et al.* (1935)	Value taken from figure
	221	443	methanol	Heierle (1935)	
Magnesium 2,4-divinylpheoporphyrin a_5 monomethyl ester	394	438	1% pyridine in acetone	Helfrich *et al*. (1999)	
	45.8	624	1% pyridine in acetone	Helfrich *et al*. (1999)	
	430	438	1% pyridine in diethyl ether	Helfrich *et al*. (1999)	
	45.5	623	1% pyridine in diethyl ether	Helfrich *et al*. (1999)	
	401	456	pyridine	Helfrich *et al*. (1999)	Regrettably incorrect *d* value (398) on the data sheet
	39.4	636	pyridine	Helfrich *et al*. (1999)	
Mutatoxanthin	208	427	diethyl ether:methylbutane:ethanol 5:5:2	Märki-Fischer *et al.* (1982)	8*S*-isomer

	246	426	diethyl ether:methylbutane:ethanol 5:5:2	Märki-Fischer *et al.* (1982)	8*R*-isomer
	224	430	ethanol	Krinsky and Goldsmith (1960)	
Myxol quinovoside	216	478	acetone	Hertzberg and Liaaen-Jensen (1969a)	
9′-*cis*-Neochrome	227	424	96% ethanol	Cholnoky *et al.* (1966)	
9′-*trans*-Neochrome	244	434	benzene	Lippert and Karrer (1956)	
	266	422	diethyl ether:methylbutane:ethanol 5:5:2	Märki-Fischer *et al.* (1984)	8′*S*-isomer
	271	422	diethyl ether:methylbutane:ethanol 5:5:2	Märki-Fischer *et al.* (1984)	8′*R*-isomer
9′-*cis*-Neoxanthin	202	447	benzene	Baumeler *et al.* (1994)	
	233	437	ethanol	Baumeler *et al.* (1994)	
	230	437	ethanol	Baumeler *et al.* (1994)	
	225	438	ethanol	Strain (1938)	
	229	438	ethanol	Strain (1938)	

All-*trans*-Neoxanthin	195	452	benzene	Baumeler and Eugster (1992)	
	176	452	benzene	Baumeler and Eugster (1992)	
	213	454	benzene	Eugster and Karrer (1957)	
	216	455	benzene	Lippert and Karrer (1956)	
	238	442	ethanol	Baumeler and Eugster (1992)	
	224	441	ethanol	Baumeler and Eugster (1992)	
	226	443	ethanol	Buchecker *et al.* (1975)	
Oscillol diquinovoside	75.0	490	10% pyridine in methanol	Hertzberg and Liaaen-Jensen (1969b)	
Peridinin	134	466	acetone	Jeffrey and Haxo (1968)	
	133	469	90% acetone	Jeffrey and Haxo (1968)	
	129	467	benzene	Jeffrey and Haxo (1968)	
	129	470	chloroform	Jeffrey and Haxo (1968)	
	145	454	diethyl ether	Jeffrey and Haxo (1968)	
	133	472	ethanol	Jeffrey and Haxo (1968)	

	135	475	ethanol	Strain *et al.* (1976)	
	147	454	10% diethyl ether in hexane	Jeffrey and Haxo (1968)	
	136	469	methanol	Jeffrey and Haxo (1968)	
	118	475	pyridine	Jeffrey and Haxo (1968)	
Pheophorbide *a*	204	412	1% pyridine in diethyl ether	Hagenbach *et al.* (1936)	
	82.4	663	1% pyridine in diethyl ether	Hagenbach *et al.* (1936)	
	177	411	tetrahydrofuran	Hynninen and Lötjönen (1980)	
	83.2	668	tetrahydrofuran	Hynninen and Lötjönen (1980)	
	192	412	tetrahydrofuran	Hynninen and Sievers (1981)	
	88.9	668	tetrahydrofuran	Hynninen and Sievers (1981)	
Pheophorbide *b*	290	431	5% pyridine in diethyl ether	Hagenbach *et al.* (1936)	
	52.5	651	5% pyridine in diethyl ether	Hagenbach *et al.* (1936)	
Pheophytin *a*	206	418	acetone	Lichtenthaler (1987)	
	48.5	653	acetone	Lichtenthaler (1987)	
	52.8	666	acetone	Watanabe *et al.* (1984)	

	122	411	80% acetone	Lichtenthaler (1987)	
	51.9	665	80% acetone	Lichtenthaler (1987)	
	131	409	80% acetone	Vernon (1960)	
	56.6	666-7	80% acetone	Vernon (1960)	
	61.0	672	benzene	Watanabe *et al.* (1984)	
	127	409	diethyl ether	Lichtenthaler (1987)	
	60.1	667	diethyl ether	Lichtenthaler (1987)	
	70.0	667	diethyl ether	Pennington *et al.* (1964)	
	132	409	diethyl ether	Smith and Benitez (1955)	
	63.7	667	diethyl ether	Smith and Benitez (1955)	
	60.4	668	diethyl ether	Watanabe *et al.* (1984)	
	126	409	diethyl ether	Zscheile and Comar (1941)	Value taken from figure
	143	417	95% ethanol	Lichtenthaler (1987)	
	42.8	662	95% ethanol	Lichtenthaler (1987)	
	206	417	methanol	Lichtenthaler (1987)	

	50.4	654	methanol	Lichtenthaler (1987)	
	182	418	90% methanol	Lichtenthaler (1987)	
	47.2	655	90% methanol	Lichtenthaler (1987)	
	139	411	tetrahydrofuran	Lötjönen and Hynninen (1983)	
	64.4	668	tetrahydrofuran	Lötjönen and Hynninen (1983)	
Pheophytin *b*	*175*	434	acetone	Lichtenthaler (1987)	
	34.2	653	acetone	Lichtenthaler (1987)	
	33.1	653	acetone	Watanabe *et al.* (1984)	
	147	436	80% acetone	Lichtenthaler (1987)	
	29.0	653	80% acetone	Lichtenthaler (1987)	
	181	436	80% acetone	Vernon (1960)	
	35.7	655	80% acetone	Vernon (1960)	
	36.5	657	benzene	Watanabe *et al.* (1984)	
	219	433	diethyl ether	Lichtenthaler (1987)	
	43.6	654	diethyl ether	Lichtenthaler (1987)	

	216	434	diethyl ether	Smith and Benitez (1955)	
	42.1	655	diethyl ether	Smith and Benitez (1955)	
	39.3	655	diethyl ether	Watanabe *et al.* (1984)	
	197	433	diethyl ether	Zscheile and Comar (1941)	Value taken from figure
	141	437	95% ethanol	Lichtenthaler (1987)	
	32.6	654	95% ethanol	Lichtenthaler (1987)	
	214	420	methanol	Lichtenthaler (1987)	
	43.5	648	methanol	Lichtenthaler (1987)	
	130	436	90% methanol	Lichtenthaler (1987)	
	32.8	653	90% methanol	Lichtenthaler (1987)	
	244	435	tetrahydrofuran	Hynninen and Lötjönen (1980)	
	49.6	654	tetrahydrofuran	Hynninen and Lötjönen (1980)	
Pyropheophytin *a*	60.3	667	diethyl ether	Pennington *et al.* (1964)	
Violaxanthin	224	454	benzene	Eugster and Karrer (1957)	
	225	453	benzene	Molnár and Szabolcs (1993)	

	160	454	chloroform	Gillam (1935)	
	254	437	diethyl ether:methylbutane:ethanol 5:5:2	Acemoglu *et al.* (1988)	
	241	438	diethyl ether:methylbutane:ethanol 5:5:2	Acemoglu *et al.* (1988)	3*R*,3′*R*
	240	444	ethanol	Karrer and Würgler (1943)	Value taken from figure
	229	443	ethanol	Strain (1938)	Value taken from figure
Zeaxanthin	231	452	acetone	Aasen and Jensen (1966)	
	234	452	acetone	Aasen and Jensen (1966)	
	218	463	benzene	Molnár and Szabolcs (1993)	
	211	464	benzene	Zechmeister and Lemmon (1944)	Value taken from figure
	174	481	carbon disulphide	Strain (1938)	Value taken from figure
	178	483	carbon disulphide	Strain (1938)	Value taken from figure
	150	460	chloroform	Gillam (1935)	
	219	462	chloroform	Strain (1938)	

	230	462	chloroform	Widmer *et al.* (1990)	
	245	450	diethyl ether:methylbutane:ethanol 5:5:2	Englert *et al.* (1991)	
	240–**245**	453	ethanol	Strain (1938)	Several absorption coefficient measurements; values taken from figures
	235	452	petroleum ether	Isler *et al.* (1956*c*)	
	235	452	petroleum ether	Isler *et al.* (1957*b*)	

References

Aasen, A.J. and Jensen, S.L. (1966). Carotenoids of Flexibacteria IV. The carotenoids of two further pigment types. *Acta Chem. Scand.* **20**, 2322–24.

Acemoglu, M., Uebelhart, P., Rey, M. and Eugster, C.H. (1988). Synthese von enantiomerenreinen Violaxanthinen und verwandten Verbindungen. *Helv. Chim. Acta* **71**, 931–56.

Akhtar, M. and Weedon, B.C.L. (1959). Carotenoids and related compounds. Part VIII. Novel syntheses of echinenone and canthaxanthin. *J. Chem. Soc.* **1959**, 4058–62.

Antia, N.J. (1965). The optical activity of fucoxanthin. *Can. J. Chem.* **43**, 302–03.

Araujo, P.W., Kavianpour, K. and Brereton, R.G. (1995). Development of a novel methodology in the determination of magnesium from chlorophyll *a* by atomic absorption spectrometry using chemometric experimental design. *Analyst* **120**, 295–98.

Baumeler, A. and Eugster, C.H. (1992). Synthese von (6*R*,all-*E*)-Neoxanthin und verwandten Allen-Carotinoiden. *Helv. Chim. Acta* **75**, 773–90.

Baumeler, A., Zerbe, O., Kunz, R. and Eugster, C.H. (1994). (6*R*,9'*Z*)-Neoxanthin: Synthese, Schmelzverhalten, Spektren und Konformationsberechnungen. *Helv. Chim. Acta* **77**, 909–30.

Bernegg, A.S. von, Heierle, E. and Almasy, F. (1935). Spektrometrische Bestimmung von Chlorophyll a, Chlorophyll b, Carotin und Xanthophyll. *Biochem. Zeitschr.* **283**, 45–52.

Bickoff, E.M., White, L.M., Bevenue, A. and Williams, K.T. (1948). Isolation and spectrophotometric characterization of four carotene isomers. *J. Assoc. Off. Agricult. Chem.* **31**, 633–46.

Bonnett, R., Mallams, A.K., Spark, A.A., Tee, J.L., Weedon, B.C.L. and McCormick, A. (1969). Carotenoids and related compounds. Part XX. Structure and reactions of fucoxanthin. *J. Chem. Soc. C* **1969**, 429–54.

Buchecker, R., Hamm, P. and Eugster, C.H. (1974). Absolute Konfiguration von Xanthophyll (Lutein). *Helv. Chim. Acta* **57**, 631–56.

Buchecker, R., Liaaen-Jensen, S. and Eugster, C.H. (1975). The identity of trollixanthin and trolliflor with neoxanthin. *Phytochemistry* **14**, 797–99.

Buchwald, M. and Jencks, W.P. (1968). Optical properties of astaxanthin solutions and aggregates. *Biochemistry* **7**, 834–43.

Bush, W.V. and Zechmeister, L. (1958). On some cleavage products of the boron trifluoride complexes of α-carotene, lycopene and γ-carotene. *J. Am. Chem. Soc.* **80**, 2991–99.

Chechak, A.J., Stern, M.H. and Robeson, C.D. (1964). Synthesis of β-carotene and certain polyenes *via* thiapyran intermediates. *J. Org. Chem.* **29**, 187–90.

Cholnoky, L., Györgyfy, K., Szabolcs, J., Weedon, B.C.L. and Waight, E.S. (1966). Foliaxanthin. *Chem. Commun.* **1966**, 404–05.

Cholnoky, L., Szabolcs, J. and Tóth, G. (1967). Untersuchungen über Carotinoidfarbstoffe, VII Reduktion von Carotinoidoxiden mit Lithiumalanat. *Liebigs Ann. Chem.* **708**, 218–23.

Clayton, R.K. (1966). Spectroscopic analysis of bacteriochlorophylls *in vitro* and *in vivo*. *Photochem. Photobiol.* **5**, 669–77.

Cohen-Bazire, G. and Sistrom, W.R. (1966). The prokaryotic photosynthetic apparatus. In *The Chlorophylls*, ed. L.P. Vernon and G.R. Seely, New York: Academic Press, pp. 313–41.

Connolly, J.S., Samuel, E.B. and Janzen, A.F. (1982). Effects of solvent on the fluorescence properties of bacteriochlorophyll *a*. *Photochem. Photobiol.* **36**, 565–74.

Davies, A.J., Khare, A., Mallams, A.K., Massy-Westropp, R.A., Moss, G.P. and Weedon, B.C.L. (1984). Carotenoids and related compounds. Part 38. Synthesis of (3*RS*,3'*RS*)-alloxanthin and other acetylenes. *J. Chem. Soc., Perkin Trans. 1* **1984**, 2147–57.

Davies, B.H. (1965). Analysis of carotenoid pigments. In *Chemistry and Biochemistry of Plant Pigments*, ed. T.W. Goodwin. London: Academic Press, pp. 489–532.

Englert, G., Kienzle, F. and Noack, K. (1977). ^{1}H-NMR.-, ^{13}C-NMR.-, UV.- und CD.-Daten von synthetischem (3*S*,3'*S*)-Astaxanthin, seinem 15-*cis*-Isomeren und einigen analogen Verbindungen. *Helv. Chim. Acta* **60**, 1209–19.

Englert, G., Noack, K., Broger, E.A., Glinz, E., Vecchi, M. and Zell, R. (1991). Synthesis, isolation, and full spectroscopic characterization of eleven (*Z*)-isomers of (3*R*,3'*R*)-zeaxanthin. *Helv. Chim. Acta* **74**, 969–82.

Entschel, R. and Karrer, P. (1958). Carotinoidsynthesen XXII. Umsetzungsprodukte des β-Carotins mit Bromsuccinimid. (Einführung von Äther- und Hydroxyl-Gruppen in den Kohlenwasserstoff.). *Helv. Chim. Acta* **41**, 402–13.

Eugster, C.H. and Karrer, P. (1955). Carotinoidsynthesen XV. Kristallisiertes *d*,*l*-α-Carotin. *Helv. Chim. Acta* **38**, 610–12.

Eugster, C.H. and Karrer, P. (1957). Taraxanthin und Tarachrom, sowie Beobachtungen über stereoisomere Trollixanthine. *Helv. Chim. Acta* **40**, 69–79.

Ganguly, J., Krinsky, N.I. and Pinckard, J.H. (1956). Isolation and nature of echinenone, a provitamin A. *Arch. Biochem. Biophys.* **60**, 345–51.

Garside, C. and Riley, J.P. (1968). The absorptivity of fucoxanthin. *Deep-Sea Res.* **15**, 627.

Gillam, A.E. (1935). Spectrometric measurements on various carotenoids. *Biochem. J.* **29**, 1831–36.

Hagenbach, A., Auerbacher, F. and Wiedemann, E. (1936). Zur Kenntnis der Lichtabsorption von Porphinfarbstoffen und über einige mögliche Beziehungen derselben zu ihrer Konstitution. *Helv. Chim. Acta* **9**, 3–26.

Hager, A. and Meyer-Bertenrath, T. (1966). Die Isolierung und quantitative Bestimmung der Carotinoide und Chlorophylle von Blättern, Algen und isolierten Chloroplasten mit Hilfe dünnschichtchromatographisher Methoden. *Planta (Berl.)* **69**, 198–217.

Hartwich, G., Fiedor, L., Simonin, I., Cmiel, E., Schäfer, W., Noy, D., Scherz, A. and Scheer, H. (1998). Metal-substituted bacteriochlorophylls. 1. Preparation and influence of metal and coordination on spectra. *J. Am. Chem. Soc.* **120**, 3675–83.

Haugan, J.A. and Liaaen-Jensen, S. (1989). Improved isolation procedure for fucoxanthin. *Phytochemistry* **28**, 2797–98.

Haugan, J.A. and Liaaen-Jensen, S. (1994). Total synthesis of acetylenic carotenoids. 2. Synthesis of (all-*E*)-(3*R*,3'*R*)-diatoxanthin and (all-*E*)-(3*R*)-7,8-didehydrocryptoxanthin. *Acta Chem. Scand.* **48**, 899–904.

Heierle, E. (1935). Blattfarbstofuntersuchungen an einer grün- und gelbblättrigen Tabak-Varietät. *Ber. Schweizerisch. Bot. Gesellsch.* **44**, 17–87.

Helfrich, M., Ross, A., King, G.C., Turner, A.G. and Larkum, A.W.D. (1999). Identification of [8-vinyl]-protochlorophyllide *a* in phototrophic prokaryotes and algae: chemical and spectroscopic properties. *Biochim. Biophys. Acta* **1410**, 262–72.

Hertzberg, S. and Liaaen-Jensen, S. (1969*a*). The structure of myxoxanthophyll. *Phytochemistry* **8**, 1259–80.

Hertzberg, S. and Liaaen-Jensen, S. (1969*b*). The structure of oscillaxanthin. *Phytochemistry* **8**, 1281–92.

Hiyama, T., Nishimura, M. and Chance, B. (1969). Determination of carotenes by thin-layer chromatography. *Anal. Biochem.* **29**, 339–42.

Holt, A.S. and Jacobs, E.E. (1954). Spectroscopy of plant pigments. II. Methyl bacteriochlorophyllide and bacteriochlorophyll. *Am. J. Bot.* **41**, 718–22.

Holt, A.S. and Morley, H.V. (1959). A proposed structure for chlorophyll *d*. *Can. J. Chem.* **37**, 507–514.

Hynninen, P.H. (1981). Mechanism of the allomerization of chlorophyll: inhibition of the allomerization by carotenoid pigments. *Z. Naturforsch.* **36 b**, 1010–16.

Hynninen, P.H. and Lötjönen, S. (1980). Preparation of phorbin derivatives from chlorophyll mixture utilizing the principle of selective hydrolysis. *Synthesis* **1980**, 539–41.

Hynninen P.H. and Lötjönen, S. (1983). Large-scale preparation of crystalline (10*S*)-chlorophylls *a* and *b*. *Synthesis* **1983**, 705–08.

Hynninen, P.H. and Sievers, G. (1981). Conformations of chlorophyll *a* and *a*′ and their magnesium-free derivatives as revealed by circular dichroism and proton magnetic resonance. *Z. Naturforsch.* **36 b**, 1000–09.

Inhoffen, H.H., Pommer, H. and Bohlmann, F. (1950*a*). Synthesen in der Carotinoid-Reihe, XIV Aufbau des β-Carotins. *Liebigs Ann. Chem.* **569**, 237–46.

Inhoffen, H.H., Pommer, H. and Westphal, F. (1950*b*). Synthesen in der Carotinoid-Reihe, XVI Eine weitere Synthese des β-Carotins. *Liebigs Ann. Chem.* **570**, 69–72.

Inhoffen, H.H., Schwieter, U. and Raspé, G. (1954). Synthesen in der Carotinoid-Reihe XXX Totalsynthese des d,l-α-Carotins, *Liebigs Ann. Chem.* **588**, 117–125.

Isler, O. and Schudel, P. (1963). Synthese und Markierung von Carotinen und Carotinoiden. *Wissensch. Veröff. Deutsch. Gesellsch. Ernähr.* **9**, 54–104.

Isler, O., Gutmann, H., Lindlar, H., Montavon, M., Rüegg, R., Ryser, G. and Zeller, P. (1956*a*). Synthesen in der Carotinoid-Reihe. 6. Mitteilung. Synthese von Crocetindialdehyd und Lycopin. *Helv. Chim. Acta* **39**, 463–73.

Isler, O., Lindlar, H., Montavon, M., Rüegg, R. and Zeller, P. (1956*b*). Synthesen in der Carotinoid-Reihe. 1. Mitteilung. Die technische Synthese von β-Carotin. *Helv. Chim. Acta* **39**, 249–59.

Isler, O., Lindlar, H., Montavon, M., Rüegg, R., Saucy, G. and Zeller, P. (1956*c*). Synthesen in der Carotinoid-Reihe 7. Mitteilung. Totalsynthese von Zeaxanthin und Physalien. *Helv. Chim. Acta* **39**, 2041–53.

Isler, O., Montavon, M., Rüegg, R. and Zeller, P. (1956*d*). Synthesen in der Carotinoid-Reihe. 5. Mitteilung. Anwendungen der Reaktion von *Whiting*. *Helv. Chim. Acta* **39**, 454–62.

Isler, O., Lindlar, H., Montavon, M., Rüegg, R., Saucy, G. and Zeller, P. (1957*a*). Synthesen in der Carotinoid-Reihe. 8. Mitteilung. Totalsynthese von Kryptoxanthin und eine weitere Synthese von Zeaxanthin. *Helv. Chim. Acta* **40**, 456–67.

Isler, O., Montavon, M., Rüegg, R. and Zeller, P. (1957*b*). Synthesen in der Carotinoid-Reihe, 9. Mitteilung. Neuer Aufbau symmetrischer Carotinoide. *Liebigs Ann. Chem.* **603**, 129–44.

Jeffrey, S.W. (1972). Preparation and some properties of crystalline chlorophyll c_1 and c_2 from marine algae. *Biochim. Biophys. Acta* **279**, 15–33.

Jeffrey, S.W. (1997). Preparation of chlorophyll standards. In *Phytoplankton Pigments in Oceanography: Guidelines to Modern Methods*, ed. S.W. Jeffrey, R.F.C. Mantoura and S.W. Wright. Paris: UNESCO Publishing, pp. 207–38.

Jeffrey, S.W. and Haxo, F.T. (1968). Photosynthetic pigments of dinoflagellates (zooxanthellae) from corals and clams. *Biol. Bull*. **135**, 149–65.

Jeffrey, S.W. and Humphrey, G.F. (1975). New spectrophotometric equations for determining chlorophylls *a*, *b*, c_1 and c_2 in higher plants, algae and natural phytoplankton. *Biochem. Physiol. Pflanzen* **167**, 191–94.

Jeffrey, S.W., Mantoura, R.F.C. and Bjørnland, T. (1997). Data for the identification of 47 key phytoplankton pigments. In *Phytoplankton Pigments in Oceanography: Guidelines to Modern Methods*, ed. S.W. Jeffrey, R.F.C. Mantoura and S.W. Wright. Paris: UNESCO Publishing, pp. 449–559.

Jensen, A. (1966). *Carotenoids of Norwegian Brown Seaweeds and of Seaweed Meals.* Norwegian Institute of Seaweed Research, Report no. 31. Trondheim: Tapir, 138 pp.

Johansen, J.E., Svec, W.A., Liaaen-Jensen, S. and Haxo, F.T. (1974). Carotenoids of the Dinophyceae. *Phytochemistry* **13**, 2261–71.

Kabbe, H.-J., Truscheit, E. and Eiter, K. (1965). Synthesen von β-Carotin und Lycopin aus Octen-(4)-dion-(2.7). *Liebigs Ann. Chem.* **684**, 14–24.

Kar, B.K. (1937). Über das Verhalten der Plastidenfarbstoffe photoperiodisch reagierender Pflanzen bei verschiedenem Lichtgenuss. *Planta* **26**, 420–62.

Karrer, P. and Rutschmann, J. (1942). Auroxanthin, ein kurzwellig absorbierender Carotinfarbstoff. *Helv. Chim. Acta* **25**, 1624–27.

Karrer, P. and Würgler, E. (1943). Absorptionsspektren einiger Carotinoide. *Helv. Chim. Acta* **26**, 116–21.

Krinsky, N.I. and Goldsmith, T.H. (1960). The carotenoids of the flagellated alga, *Euglena gracilis*. *Arch. Biochem. Biophys.* **91**, 271–79.

Kuhn, R., Stene, J. and Sörensen, N.A. (1939). Über die Verbreitung des Astaxanthins im Tier- und Pflanzenreich. *Ber. Deutsch. Chem. Gesellsch.* **72**, 1688–701.

Lenz, J. and Zeitzschel, B. (1968). Zur Bestimmung des Extinktionskoeffizienten für Chlorophyll a in Methanol. *Kieler Meeresforsch.* **24**, 41–50.

Lichtenthaler, H.K. (1987). Chlorophylls and carotenoids: pigments of photosynthetic biomembranes. *Meth. Enzymol.* **148**, 350–82.

Lippert, M. and Karrer, P. (1956). Ein zweites Pigment aus den Blüten von Trollius europaeus: Trolliflor. *Helv. Chim. Acta* **39**, 698–701.

Loeber, D.E., Russell, S.W., Toube, T.P., Weedon, B.C.L. and Diment, J. (1971). Carotenoids and related compounds. Part XXVIII. Synthesis of zeaxanthin, β-cryptoxanthin, and zeinoxanthin (α-cryptoxanthin). *J. Chem. Soc. C* **1971**, 404–08.

Lötjönen, S. and Hynninen, P.H. (1983). An improved method for the preparation of (10*R*)- and (10*S*)-pheophytins *a* and *b*. *Synthesis* **1983**, 708–10.

Mackinney, G. (1935). On the plastid pigments of marsh dodder. *J. Biol. Chem.* **112**, 421–24.

Mackinney, G. (1941). Absorption of light by chlorophyll solutions. *J. Biol. Chem.* **140**, 315–22.

Manchard, P.S., Rüegg, R., Schwieter, U., Siddons, P.T. and Weedon, B.C.L. (1965). Carotenoids and related compounds. Part XI. Syntheses of δ-carotene and ε-carotene. *J. Chem. Soc.* **1965**, 2019–26.

Märki-Fischer, E., Buchecker, R., Eugster, C.H., Englert, G., Noack, K. and Vecchi, M. (1982). Absolute Konfiguration von Antheraxanthin, "cis-Antheraxanthin" und der diastereomeren Mutatoxanthine. *Helv. Chim. Acta* **65**, 2198–211.

Märki-Fischer, E., Buchecker, R. and Eugster, C.H. (1984). Trennung und absolute Konfiguration der C(8)-eipimeren (all-*E*)-Neochrome (Trollichrome) und -Dinochrome. *Helv. Chim. Acta* **67**, 461–66.

Mayer, H. and Rüttimann, A. (1980). Synthese von optisch aktiven, natürlichen Carotinoiden und strukturell verwandten Naturprodukten IV. Synthese von (3*R*,3'*R*,6'*R*)-Lutein. *Helv. Chim. Acta* **63**, 1451–55.

Molnár, P. and Szabolcs, J. (1993). (*Z/E*)-Photoisomerization of C_{40}-carotenoids by iodine. *J. Chem. Soc., Perkin Trans. 2* **1993**, 261–66.

Nürrenbach, A. and Pommer, H. (1969). Über die Umsetzung von Nitroso-Verbindungen mit Phosphoryliden. *Liebigs Ann. Chem.* **721**, 34–42.

Parsons, T.R. and Strickland, J.D.H. (1963). Discussion of spectrophotometric determination of marine-plant pigments, with revised equations for ascertaining chlorophylls and carotenoids. *J. Mar. Res.* **21**, 155–63.

Pennington, F.C., Strain, H.H., Svec, W.A. and Katz, J.J. (1964). Preparation and properties of pyrochlorophyll *a*, methyl pyrochlorophyllide *a*, pyropheophytin *a*, and methyl pyropheophorbide *a* derived from chlorophyll by decarbomethoxylation. *J. Am. Chem. Soc.* **86**, 1418–26.

Permentier, H.P., Schmidt, K.A., Kobayashi, M., Akiyama, M., Hager-Braun, C., Neerken, S., Miller, M. and Amesz, J. (2000). Composition and optical properties of reaction centre core complexes from the green sulfur bacteria *Prosthecochloris aestuarii* and *Chlorobium tepidum*. *Photosynth. Res.* **64**, 27–39.

Petracek, F.J. and Zechmeister, L. (1956*a*). Reaction of β-carotene with N-bromsuccinimide: the formation and conversions of some polyene ketones. *J. Am. Chem. Soc.* **78**, 1427–34.

Petracek, F.J. and Zechmeister, L. (1956*b*). The structure of canthaxanthin. *Arch. Biochem. Biophys.* **61**, 137–39.

Porra, R.J. (1990). A simple method for extracting chlorophylls from the recalcitrant alga, *Nannochloris atomus*, without formation of spectroscopically-different magnesium-rhodochlorin derivatives. *Biochim. Biophys. Acta* **1019**, 137–41.

Porra, R.J., Thompson, W.A. and Kriedemann, P.E. (1989). Determination of accurate extinction coefficients and simultaneous equations for assaying chlorophylls *a* and *b* extracted with four different solvents: verification of the concentration of chlorophyll standards by atomic absorption spectroscopy. *Biochim. Biophys. Acta*. **975**, 384–94.

Repeta, D.J. and Bjørnland, T. (1997). Preparation of carotenoid standards. In *Phytoplankton Pigments in Oceanography: Guidelines to Modern Methods*, ed. S.W. Jeffrey, R.F.C. Mantoura and S.W. Wright. Paris: UNESCO Publishing, pp. 239–60.

Rüegg, R., Schwieter, U., Ryser, G., Schudel, P. and Isler, O. (1961). Synthesen in der Carotinoid-Reihe 17. Mitteilung. γ-Carotin sowie *d,l*-α- und β-Carotin aus Dehydro-β-apo-12'-carotinal(C_{25}). *Helv. Chim. Acta* **44**, 985–93.

Saitoh, K., Awaka, I. and Suzuki, N. (1993). Separation of chlorophyll c_1 and c_2 by reversed-phase high-performance liquid chromatography. *J. Chromatogr. A* **653**, 247–51.

Sauer, K., Smith, J.R.L. and Schultz, A.J. (1966). The dimerization of chlorophyll a, chlorophyll b and bacteriochlorophyll in solution. *J. Am. Chem. Soc.* **88**, 2681–88.

Schwieter, U., Bolliger, H.R., Chopard-dit-Jean, L.H., Englert, G., Kofler, M., König, A., Planta, C.v., Rüegg, R., Vetter, W. and Isler, O. (1965). Synthesen in der Carotinoid-Reihe 19. Mitteilung: Physikalische Eigenschaften der Carotine. *Chimia* **19**, 294–302.

Shedbalkar, V.P. and Rebeiz, C.A. (1992). Chloroplast biogenesis: Determination of the molar extinction coefficients of divinyl chlorophyll *a* and *b* and their pheophytins. *Anal. Biochem*. **207**, 261–66.

Smith, J.H.C. (1936). Carotene. X. A comparison of absorption spectra measurements on α-carotene, β-carotene and lycopene. *J. Am. Chem. Soc.* **58**, 247–55.

Smith, J.H.C. and Benitez, A. (1955). Chlorophylls: Analysis in plant materials. In *Modern Methods of Plant Analysis*, Vol. 4, ed. K. Paech and M.V. Tracey. Berlin: Springer, pp. 142–96.

Strain, H.H. (1938). Leaf xanthophylls. Washington: Carnegie Institution of Washington, Publication No 490, 147 pp.

Strain, H.H. and Svec, W.A. (1966). Extraction, separation, estimation, and isolation of chlorophylls. In *The Chlorophylls*, ed. L.P. Vernon and G.R. Seely. New York: Academic Press, pp. 21–66.

Strain, H.H., Thomas, M.R. and Katz, J.J. (1963). Spectral absorption properties of ordinary and fully deuterated chlorophylls *a* and *b*. *Biochim. Biophys. Acta* **75**, 306–11.

Strain, H.H., Svec, W.A., Wegfahrt, P., Rapoport, H., Haxo. F.T., Norgård, S., Kjøsen, H. and Liaaen-Jensen, S. (1976). Algal carotenoids. XIV. Structural studies on peridinin. Part 1. Structure elucidation. *Acta Chem. Scand. B* **30**, 109–20.

Surmatis, J.D., Gibas, J. and Thommen, R. (1969). The synthesis of 1-(2,6,6-trimethyl-1-cyclohexen-1-yl)-18-(2,6,6-trimethyl-2-cyclohexen-1-ylidene)-3,7,12,16-tetramethyl-2,4,6,8,10,12,14,16,18-octadecanonaene and its rearrangement to *trans*-β-carotene. *J. Org. Chem.* **34**, 3093–41.

Surmatis, J.D., Walser, A., Gibas, J., Schwieter, U. and Thommen, R. (1970). New methods for the synthesis of oxygenated carotenoids. *Helv. Chim. Acta.* **53**, 974–90.

Trurnit, H.J. and Colmano, G. (1959). Chloroplast studies I. Absorption spectra of chlorophyll monolayers at liquid interfaces. *Biochim. Biophys. Acta* **31**, 434–47.

Tscharner, C., Eugster, C.H. and Karrer, P. (1957). Synthese der optisch aktiven α-carotine. Carotinoidsynthesen XX. *Helv. Chim. Acta* **40**, 1676–77.

Vernon, L.P. (1960). Spectrophotometric determination of chlorophylls and pheophytins in plant extracts. *Anal. Chem.* **32**, 1144–50.

Warren, C.K. and Weedon, B.C.L. (1958). Carotenoids and related compounds. Part VII. Synthesis of canthaxanthin and echinenone. *J. Chem. Soc.* **1958**, 3986–93.

Watanabe, T., Hongu, A., Honda, K., Nakazato, M., Konno, M. and Saitoh, S. (1984). Preparation of chlorophylls and pheophytins by isocratic chromatography. *Anal. Chem.* **56**, 251–56.

Weigl, J.W. (1953). Concerning the absorption spectrum of bacteriochlorophyll. *J. Am. Chem. Soc.* **75**, 999–1000.

Wellburn, A.R. (1994). The spectral determination of chlorophylls *a* and *b*, as well as total carotenoids, using various solvents with spectrophotometers of different resolution. *J. Plant Physiol.* **144**, 307–13.

Widmer, E., Zell, R., Broger, E.A., Crameri, Y., Wagner, H.P., Dinkel, J., Schlageter, M. and Lukáč, T. (1981*a*). Technische Verfahren zur Synthese von Carotinoiden und verwandten Verbindungen aus 6-Oxo-isophoron. II. Ein neues Konzept für die Synthese von (3*RS*,3'*RS*)-Astaxanthin. *Helv. Chim. Acta* **64**, 2436–46.

Widmer, E., Zell, R., Lukáč, Casadei, M., Schönholzer, P. and Broger, E.A. (1981*b*). Technische Verfaren zur Synthese von Carotinoiden und verwandten Verbindungen aus 6-Oxo-isophoron. I. Modifizierung der *Kienzle-Mayer*-Synthese von (3*S*,3'*S*)-Astaxanthin. *Helv. Chim. Acta* **64**, 2405–18.

Widmer, E., Soukup, M., Zell, R., Broger, E., Wagner, H.P. and Imfeld, M. (1990). Technical procedures for the syntheses of carotenoids and related compounds from 6-oxo-isophorone: synthesis of (3*R*,3'*R*)-zeaxanthin. Part I. *Helv. Chim. Acta* **73**, 861–67.

Wintermans, J.F.G.M. and Mots, A.D. (1965). Spectrophotometric characteristics of chlorophylls *a* and *b* and their pheophytins in ethanol. *Biochim. Biophys. Acta* **109**, 448–53.

Zechmeister, L. and Lemmon, R.M. (1944). Contribution to the stereochemistry of cryptoxanthin and zeaxanthin. *J. Am. Chem. Soc.* **66**, 317–22.

Zechmeister, L., LeRosen, A.L., Schroeder, W.A., Polgár, A. and Pauling, L. (1943). Spectral characteristics and configuration of some stereoisomeric carotenoids including prolycopene and pro-γ-carotene. *J. Am. Chem. Soc.* **65**, 1940–51.

Zeller, P., Bader, F., Lindlar, H., Montavon, M., Müller, P., Rüegg, R., Ryser, G., Saucy, G., Schaeren, S.F., Schwieter, U., Stricker, K., Tamm, R., Zürcher, P. and Isler, O. (1959). Synthesen in der Carotinoid-Reihe 13. Mitteilung. Synthese von Canthaxanthin. *Helv. Chim. Acta* **42**, 841–47.

Ziegler, R. and Egle, K. (1965). Zur quantitativen Analyse der Chloroplastenpigmente I. Kritische Überprüfung der spektralphotometrischen Chlorophyll-Bestimmung. *Beitr. Biol. Planzen* **41**, 11–37.

Zscheile, F.P. and Comar, C.L. (1941). Influence of preparative procedure on the purity of chlorophyll components as shown by absorption spectra. *Bot. Gaz.* **102**, 463–81.

Zscheile, F.P., White, J.W., Beadle, B.W. and Roach, J.R. (1942). The preparation and absorption spectra of five pure carotenoid pigments. *Plant Physiol.* **17**, 331–46.