Lecture 6a: Pigments and Photosynthesis

Theory

Smit, A. J.
University of the Western Cape

Table of contents

1 Introduction: Pigments and Photosynthesis . . . 2
2 Overview of Pigments in Photosynthetic Organisms . . . 3
3 Absorption Properties of Chlorophyll-a and Accessory Pigments . . . 3
4 The Green Gap and Accessory Pigments . . . 5
5 Classification and Function of Pigments . . . 6
6 What is Photosynthesis? . . . 7
7 The Photosynthesis-Irradiance (PI) Curve . . . 8
8 Effects of Environmental Stress . . . 9
9 Absorption Spectrum vs Action Spectrum . . . 11
Bibliography . . . 12

1 Introduction: Pigments and Photosynthesis

Good morning everyone, welcome back to BDC223. Today we're going to follow on from our lectures on light, and we're going to be talking about pigments and photosynthesis. Much of today's discussion, and also the next couple of lectures about pigments as well as chromatic adaptation, is based on two papers I need you to read. The papers are both on iKamva; you can find them there. Please read them while working through these lectures—it's quite important that you understand their content. Everything I'm going to talk about today will be explained in a lot greater detail in those two papers.

2 Overview of Pigments in Photosynthetic Organisms

- In order to fully utilise all available light energy, algae and plants have a range of accessory photosynthetic pigments in addition to chlorophyll-*a*.
- All primary producers use chlorophyll-*a* to convert light energy into a chemical form. Chl-*a* is the only pigment that can provide the chemical energy necessary for photosynthesis. It is contained within the light-harvesting complexes, together with other pigments.
- Chl-*a* have absorption peaks situated mainly at 440 nm (blue light) and 675 nm (red light) allowing primary producers to absorb light in all habitats, terrestrial or marine.
- [see Fig. 4.1, Lobban and Harrison (1994), p. 125 for absorption spectra]

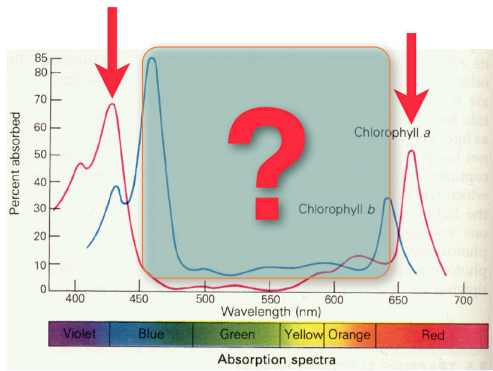
So, in order to exploit the light available in the environment, plants and algae—indeed, all photo-oxygenic organisms—rely on a range of pigments that extract energy from light and convert it into chemical potential energy in the process of photosynthesis.

The predominant pigment in all photo-oxygenic production on Earth, and in all plants, algae, and cyanobacteria, is a molecule called chlorophyll-a. The chlorophyll-a pigment takes light energy and converts it into chemical energy. It is the only pigment that plays such a central role in photosynthesis. There are many other pigments called accessory pigments; they do not directly drive photosynthesis but support light harvesting.

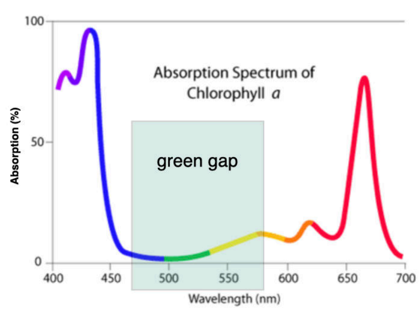
3 Absorption Properties of Chlorophyll-a and Accessory Pigments

Chlorophyll-a absorbs light mainly in the blue and red regions. In the previous lecture you saw that visible light falls between roughly 390 nm to around 760 nm. That's the range of photosynthetically active radiation. However, within that range, not all light is equally effective at driving photosynthesis. This is because chlorophyll-a can maximally absorb light at 440 nm (blue light) and 675 nm (red light).

Regardless of where these primary producers are—on land, in water, or elsewhere—they are sensitive to blue and red light. If they do not have sufficient light at precisely those wavelengths, their rate of photosynthesis will be impaired.



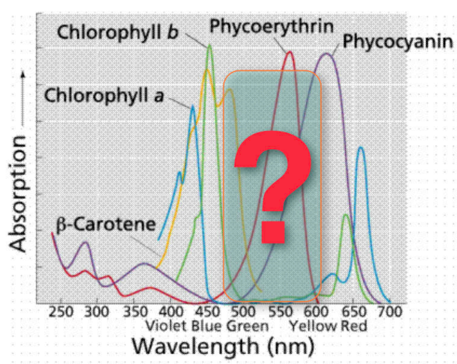
Here are some graphs (Slide reference) that show the absorption for chlorophyll-a and chlorophyll-b. Chlorophyll-a, shown as the red line, has two main peaks: one around 425 nm (blue) and one in the red region around 660 to 675 nm. Chlorophyll-b has similar peaks but they are shifted: the blue peak sits nearer to 460 nm, closer to green, and the red peak falls slightly toward the orange region.



Chlorophyll-b does not drive photosynthesis directly, but it can harvest light and pass that energy to chlorophyll-a, thus broadening the range of light absorbed and utilised for photosynthesis. You'll notice that, in the middle of these spectra, there is a gap—a region where light is available yet not absorbed by chlorophyll-a or b. This is often referred to as the "green gap" and is the reason why plants appear green: green light is not absorbed by the major photosynthetic pigments in most leaves, so it is reflected back into the environment and to our eyes.

4 The Green Gap and Accessory Pigments

Accessory pigments



Plants have evolved various pigments to fill that green gap. Among the most notable of these are carotenoids, which include beta-carotene, and the phycobilins, such as phycoerythrin and phycocyanin. Carotenoids are also the pigments responsible for the orange colour in carrots, as indicated by the orange line on many absorption spectra.

The carotenoids and phycobilins absorb light in the green gap and pass that energy on to chlorophyll-a, enabling photosynthesis that would otherwise not occur at those wavelengths. These are called accessory pigments because they complement the absorption range of chlorophyll-a and make photosynthesis more effective in sub-optimal light conditions.

At first glance, the diversity of accessory pigments appears as vast as the diversity of light climates in the ocean, on land, and in freshwater. However, later experiments—especially those by Engelman, Haxo, and Blinks (to be discussed in your papers)—demonstrate that the diversity of accessory pigments does not necessarily correspond to the diversity of environmental light conditions.

5 Classification and Function of Pigments

- Plants have a wide range of accessory pigments that pass light on to chl-*a*.
- The diversity of accessory pigments initially seems to complement the diversity of light climates in the oceans and other aquatic systems.
- All pigments fall within the classes **chlorophylls**, **carotenoids** (carotenes and xanthophylls) and **phycobilins** (or phycobiliproteins). There are more than 40 pigments in photoautotrophs.
- Different chlorophylls (especially chl-*a*) bind to proteins in different ways, thus further increasing variation in their absorption spectra, especially around the red peak.

There are three main pigment classes:

1. **Chlorophylls** – The major photosynthetic pigments. Chlorophyll-a is primary, with chlorophylls-b and -c acting as accessory pigments that transfer absorbed energy to chlorophyll-a.
2. **Carotenoids** – Includes beta-carotene and xantho-phylls, which also serve as accessory pigments.
3. **Phycobilins** – Reddish or purplish pigments, including phycocyanin and phycoerythrin, mainly found in certain algae and cyanobacteria.

Across all photoautotrophs, there are more than forty pigments involved. They bind differently to the proteins making up the photosynthetic machinery, expanding the plant's ability to absorb different wavelengths, especially in the green gap, and maintain high photosynthetic efficiency in a range of environments.

Summarise pigments in Lobban and Harrison (1997)

Algal class	Principal pigments
Bacillariophyceae	Chl *a*; chl *c*; *β*-carotene; fucoxanthin; diatoxanthin; diadinoxanthin
Dinophyceae	Chl *a*; chl c_2; *β*-carotene; peridinin; neoperidinin
Phaeophyceae	Chl *a*; chl c_1; chl c_2; *β*-carotene; fucoxanthin
Raphidophyceae	Chl *a*; chl *c*; diatoxanthin; diadinoxanthin; heteroxanthin; fucoxanthin
Cryptophyceae	Chl *a*; chl c_2; *α*-carotene; diatoxanthin; phycoerythrin; phycocyanin
Euglenophyceae	Chl *a*; chl *b*; *β*-carotene; astaxanthin; antheraxanthin; diadinoxanthin; neoxanthin
Chlorophyceae	Chl *a*; chl *b*; *α*, *β* and *γ*-carotene; lutein, siphonoxanthin; siphonein
Charophyceae	Chl *a*; chl *b*; *α*, *β* and *γ*-carotene; various xanthophylls
Prasinophyceae	Chl *a*; chl *b*; *β* carotene; siphonoxanthin; siphonein

(after South and Whittick, 1987)

Especially in algae, the types of pigments present can indicate taxonomic relationships and phylogenetic heritage. By extracting pigments from a seawater sample, for example, one can deduce the classes of algae present. Similar underpinnings occur in terrestrial plants, with certain pigments associated with specific plant types.

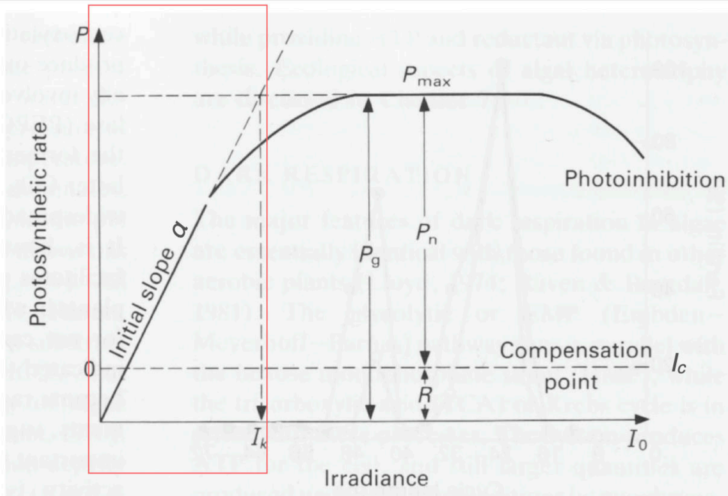
6 What is Photosynthesis?

Photosynthesis is the conversion of light energy—radiant energy—into chemical potential energy. It drives carbon fixation: uptake of CO_2 from the environment, splitting water, and releasing oxygen as a byproduct. The reactions occur in the photosystems I and II.

As a function of light intensity, photosynthesis responds with an increased rate—to a point. This relationship is described by the photosynthesis-irradiance (PI) curve.

7 The Photosynthesis-Irradiance (PI) Curve

What is photosynthesis?



The PI curve (Slide reference):

- **Y-Axis**: Rate of photosynthesis, measured by carbon incorporation (e.g., mg C m^{-2} s^{-1}, mg C m $^{-2}$ hr^{-1}, or mg C m^{-2} day^{-1}).
- **X-Axis**: Irradiance (light intensity).

Photosynthesis: PI parameters

- Photosynthetic rate (*P*) depends on the amount of irradiance (*I*) absorbed; this relationship is modeled by a *P-I* curve with the following parameters:
  - I_c: the compensation point where *P* = respiration, *R*
  - *α*: the initial slope of the curve which is an indication of quantum yield (temperature independent)
  - P_{max}: at higher irradiances, where *P* becomes saturated
  - I_k: saturating irradiance; defined as the point at which the extrapolated initial slope intersects P_{max}
- Neither I_c nor I_k are correlated with functional form

Initially, the PI curve is linear: as irradiance increases, photosynthesis increases at a rate defined by the slope α (alpha). Alpha reflects the plant's sensitivity to changes in irradiance. A steep alpha (steep slope) means more sensitivity to small changes in light; a shallow slope indicates less sensitivity and a need for greater changes in light intensity to affect photosynthesis rate.

At a certain point, the rate reaches saturation, denoted as I_k. This occurs where the extrapolated horizontal maximum rate (P_{max}) intersects with the linear part of the curve. Beyond this, increasing light does not increase photosynthetic rate since all the photosynthetic machinery is working at full capacity—much like pressing a car accelerator to the floor when the engine cannot go faster.

Should irradiance keep increasing, photosynthesis can decline—a phenomenon called photoinhibition. Here, excessive light can cause actual damage, or trigger protective mechanisms within the photosynthetic apparatus to prevent damage, analogous to running a car engine past its operating limits.

Respiration occurs at all times, consuming oxygen, while photosynthesis (in the presence of light) produces it. At low light, the rate of oxygen production by photosynthesis is less than the rate of consumption by respiration, resulting in net negative oxygen production. The light compensation point is the irradiance where net oxygen production is zero.

Net photosynthesis: Above the compensation point—positive net oxygen evolution.
Gross photosynthesis: Total oxygen produced, regardless of respiration.

Understanding these parameters—the light compensation point, α, P_{max}, I_k, etc.—is crucial. We'll revisit this concept in practical sessions where you will fit models to real data.

8 Effects of Environmental Stress

- P_{max} is a function of the carbon-fixation processes of photosynthesis, and is therefore affected by factors such as temperature and nutrient (N, P, C) availability (usually there is a $+^{ve}$ linear relationship).
- Adjustments in pigment concentrations because of changes in PFD usually leads to changes in α and P_{max}. The light compensation point may also be affected.

P_{max} represents the maximum photosynthetic capacity, which is influenced by many stresses, including thermal stress, nutrient stress, and light stress. Any of these can reduce a plant's capacity to sustain P_{max}, and a reduction in this parameter is often the first sign of environmental stress. Measuring these rates gives insights into how and when plants become stressed.

- I_c: 2 - 11 μmol m^{-2}.s^{-1} in shallow water, but may be much lower deeper down.
- I_k: 400 - 600 μmol m^{-2}.s^{-1} in intertidal habitats; 150 - 250 μmol m^{-2}.s^{-1} for upper to mid-sublittoral species; < 100 μmol m^{-2}.s^{-1} for deeper species. Photosynthesis in diatoms under ice may be saturated at 5 μmol m^{-2}.s^{-1} and may becomes photoinhibited at 25 μmol m^{-2}.s^{-1}.
- Photoinhibition may occur at high irradiances, especially in vertically mixed phytoplankton, intertidal macroalgae that experience desiccation stress; this involved damage to some components of the photosystems, such as membrane electron transport proteins.

Here are some indicative values (Slide reference):

- Intertidal environments: light saturation might occur at $400\text{–}600 \mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$
- Sublittoral species (deeper): saturated at $150\text{–}250 \mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$
- As depth increases, saturation occurs at progressively lower irradiances.
- Some deep-water plants can become photoinhibited at what would seem to us like relatively dim light.

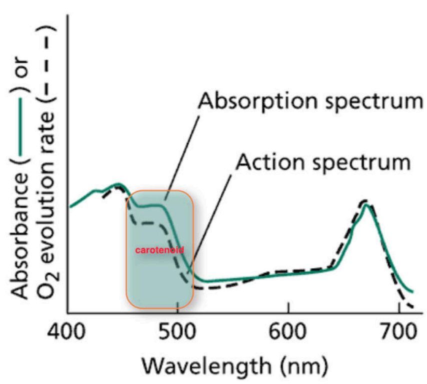
These values—I_C, I_K, P_{max}, α—vary among species, being determined both by environmental adaptation and genetic heritage, and thus serve as good indicators of a plant's typical habitat and stress response.

9 Absorption Spectrum vs Action Spectrum

- **Absorption spectrum:** the measure of the amount of light energy absorbed at each discrete wavelength over a range of wavelength.
- **Action spectra:** critical to the development of our current understanding of photosynthesis.
  - An action spectrum is a graph of the magnitude of the biological effect observed as a function of wavelength.
  - Examples of effects measured by action spectra are oxygen evolution.

Before moving on, it's critical to distinguish the absorption spectrum from the action spectrum.

- **Absorption spectrum**: Measures the amount of light absorbed by all pigments at every wavelength—essentially, how much light is not reflected or transmitted.
- **Action spectrum**: For each wavelength, measures the biological effect—oxygen evolution rate—that results from absorption.



"If the pigments used to obtain the absorption spectrum are the same as those that cause the response, the absorption and action spectra will match. In the example shown here, the action spectrum for oxygen evolution matches the absorption spectrum of intact chloroplasts quite well, indicating that light absorption by the chlorophylls mediates oxygen evolution. Discrepancies are found in the region of carotenoid absorption, from 450 to 550 nm, indicating that energy transfer from carotenoids to chlorophylls is not as effective as energy transfer between chlorophylls." (Plant Physiology online, Chapter 7; http://3e.plantphys.net/)

Typically, the action and absorption spectra match well, but not perfectly. For instance, between about 450 and 500 nm, there is a mismatch. This occurs because, beyond the optimal absorption peak of chlorophyll-a, carotenoids start absorbing light. While they can capture light within this region, they are less efficient at passing the energy to chlorophyll-a, resulting in a lower action than absorption value.

This demonstrates that the ability of accessory pigments to pass energy to chlorophyll-a is not perfectly efficient; some energy is lost in the process. Nonetheless, the presence of carotenoids extends the range in which photosynthesis can be driven by chlorophyll-a.

In summary, accessory pigments are essential in harvesting a broader range of light and making photosynthesis effective under varied light environments, even if energy transfer from accessory to primary pigments is not perfectly efficient.

Bibliography