Maintaining Water Quality for Healthy Aquarium Plants

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Plant care profiles give ranges for parameters including light, CO2, pH, and hardness. This document provides some details about these parameters.

Here are some photos of my planted aquariums before I converted to marine (saltwater). My favorite aquatic plants are Cabomba, Cryptocoryne, Amazon Sword, Java Fern, Ludwigia, and Apongeton ulvaceous.

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125-Gallon Tank

20-Gallon Tank

The setup I used for the 125-gallon tank is described in Appendix A.

I have found that keeping most aquarium plants healthy is much more difficult than keeping the fish healthy. I started with a regular fish-only aquarium and typical fluorescent light tubes (T8 size) and tried planting various types of plants. I found that most of the plants lived for a few weeks, but eventually died. I decided there was not enough light so I added two 96-watt compact fluorescent bulbs and that helped the plants grow better. With the brighter light I started having a different problem. The aquarium pH jumps up dramatically to overly high pH levels for both the fish and plants. To fix this problem I started adding acid (pH down, hydrochloric acid) to the tank every day. I started buying big bottles of pH down. It was very inconvenient to do this every day and I sometimes spilled acid on my skin and clothes. So, I thought there must be a better way. I researched in detail about what was going on with the plants and the pH, and the recommended setup for growing plants. It helps to understand the detailed science behind what is going on with the plants and the water chemistry. I apologize if this discussion is too technical, but I think it is helpful to know the details. I will start with more general information and add more detail as I go on.

Plants are largely made of carbon and water. For plants to grow they need a source of carbon and a source of energy. Photosynthesis is a key process used by plants to grow. There are two types of photosynthesis, oxygenic and anoxygenic. The oxygenic photosynthesis produces oxygen and the anoxygenic does not. The aquatic plant photosynthesis of interest is oxygenic. During oxygenic photosynthesis, light energy transfers electrons from water (H_2O) to carbon dioxide (CO_2), which produces carbohydrates. In this transfer, the CO_2 is "reduced," or receives electrons, and the water becomes "oxidized," or loses electrons. Ultimately, oxygen is produced along with carbohydrates. Oxygenic photosynthesis is written as follows:

$$6CO_2 + 12H_2O + \text{Light Energy} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

Here, six molecules of carbon dioxide (CO_2) combine with 12 molecules of water (H_2O) using light energy. The result is the formation of a single carbohydrate molecule ($C_6H_{12}O_6$, or glucose) along with six molecules each of breathable oxygen and water.

The carbohydrate (glucose/sugar) is used by the plant, along with other nutrients and water to grow. The light energy needs to be above a certain threshold level for the photosynthesis to take place. The rate of photosynthesis will increase with increasing light levels up to a threshold value which supports the maximum rate. The rate will also be limited by the amount of carbon dioxide available. Some plants can only use the dissolved carbon dioxide available at the leaves to grow. If enough CO_2 is not directly available, some plants can convert bicarbonate (HCO_3) anions in the water to carbon dioxide for photosynthesis.

The pH of the water is the concentration of hydrogen ions available in the water. The term pH stands for power of hydrogen ions (cations or positive charge ions, with fewer electrons than protons). A neutral pH value of 7 has a balance of positive hydrogen ions with negative ions (anions) present in the water. The pH scale is exponential. This means that if the pH changes by 1 (7 to 6, for example), the hydrogen ion concentration changes by a factor of 10. A change of 2 represents a concentration change of a factor of 10 squared or 100. If you start with pure water, the carbon dioxide in the air will then dissolve into the water to form carbonic acid and the resulting pH will be about 3.6. Chemicals would generally then be added to the water to increase the pH to be closer to neutral, 7.

So why were the plants making my aquarium pH so high? The strong light makes the plants photosynthesize, extracting carbon dioxide from the water and removing the carbonic acid. The minerals in the water that were previously balancing the carbonic acid then become unbalanced and result in a high pH (alkaline). Adding acid temporarily restores the balance, but the plants just continue to extract CO_2 and make the pH go up again.

The only practical solution to this problem is to provide a source of additional CO_2 to the aquarium water. Note that depending on the types of plants and the amount of light they need, the problem can be lessened by reducing the strength of the light. I am assuming you want to make your plants thrive with lots of light and enable growth of a wide variety of plant types. A high-tech way of adding CO_2 is installing a CO_2 injection system. This is what I did and it worked great. The ideal system includes the following components: a CO_2 tank, regulator needle valve, on/off solenoid, pH controller, bubble counter, CO_2 reactor chamber, CO_2 tubing, power head, water tubing, and a water flow valve. I found a kit that included everything except the CO_2 tank. A CO_2 tank can generally be supplied by a welding supply store.

The controller has a sensor that measures the pH in the water. If the pH is above a set value, the controller turns on the CO2 supply from the CO2 tank. The CO2 flows at a rate set by the needle valve through the bubble counter tube and into a CO2 reaction chamber. The CO2 reaction chamber has water from the aquarium flowing through the chamber in the opposite direction as the CO2 bubbles where the CO2 mixes with the water and is returned to the aquarium. See Appendix A for additional information.

Another complication involves trying to keep the CO2 dissolved in the water. After going to all this trouble to get the CO2 in the water, it is desired to try to keep it from just evaporating out again. If the water is vigorously aerated, the rate of CO2 removal will increase. It is recommended to avoid having a filter return pump that pours water through air into the water from above. I have found that to keep the fish alive, either water pouring in like this or a protein extraction device is needed to remove the waste proteins that accumulate on the water surface (looks like an oil slick). If this waste is not removed from the surface, the fish will die. I use a surface protein extraction device on my fresh water aquariums.

The fish and plants also need sufficient oxygen to survive. Plants also breathe in addition to photosynthesizing. The breathing process takes in oxygen and puts out CO2. At night, without light, the plants just breathe so they are putting out CO2 and taking in oxygen instead of the reverse. The optimum oxygen (O2) level at which fish and plants thrive is between 5 to 7 milligrams of O2 per quart pf water.

The main problem I had with my CO2 injection is that there was no audible alarm for when the pH went out of a safe range. When the CO2 canister ran out of CO2, the pH would shoot up. I would generally only notice after a day or two when all the plants started to die. Another difficulty is noticing if the CO2 is leaking in the tubing/connections since CO2 does not have any odor or color. A CO2 leak can cause the tank to run out sooner than necessary, wasting money. Eventually the pH sensor wore out and I stopped growing all but the hardiest plants (Cryptocoryne, Amazon Swords, and Java Fern). One other problem I had was a big Plecostomus (Pleco) that decided he loved to eat my beautiful Cabomba plants. This was not a problem at first since the Cabomba was growing even faster than the fish could eat it. However, when the CO2 ran out before I noticed, the Pleco ate all the remaining Cabomba faster than it could grow back.

So how do you know how much CO2 is in the water and how much is enough? An optimum CO2 level is about 15 milligrams per liter of water (mg/l). A good range for CO2 is between 10 and 20 mg/l. The level of CO2 can be estimated by measuring the carbonate hardness and the pH of the water. The CO2 level is directly related according to the table below:

pH	6.0	6.2	6.4	6.6	6.8	7.0	7.2	7.4	7.6	7.8	8.0
KH											
0.5	15	9.3	5.9	3.7	2.4	1.5	.93	.59	.37	.24	.15
1.0	30	18.6	11.8	7.4	4.7	3.0	1.7	1.2	.74	.47	.30
1.5	44	28	17.6	11.1	7.0	4.4	2.8	1.8	1.11	.70	.44
2.0	59	37	24	14.8	9.4	5.9	3.7	2.4	1.48	.94	.59

2.5	73	46	30	18.5	11.8	7.3	4.6	3.0	1.85	1.18	.73
3.0	87	56	35	22	14.0	8.7	5.6	3.5	2.2	1.40	.87
3.5	103	65	41	26	16.4	10.3	6.5	4.1	2.6	1.64	1.03
4.0	118	75	47	30	18.7	11.8	7.5	4.7	3.0	1.87	1.18
5.0	147	93	59	37	23	14.7	9.3	5.9	3.7	2.3	1.47
6.0	177	112	71	45	28	17.7	11.2	7.1	4.5	2.8	1.77
8.0	240	149	94	59	37	24	14.9	9.4	5.9	3.7	2.4
10.	300	186	118	74	47	30	18.6	11.8	7.4	4.7	3.0
15.	440	280	176	111	70	44	28	17.6	11.1	7.0	4.4
20.	590	370	240	148	94	59	37	24	14.8	9.4	5.9

CO_2 mg/liter

The CO2 levels in red in the table are levels that are too high for fish (> 30 mg/l). Too high a concentration of CO2 in the water prevents the fish from breathing properly since they can't get the CO2 out of their gills.

The CO2 concentration depends on the pH and the carbonate hardness (KH). I originally intended to write this to explain water hardness (partly to myself). The area of water hardness has been extremely confusing to me for a long time. The number of different measurement techniques, units, definitions, types, and misnomers are large. There is general hardness, total hardness, carbonate hardness, noncarbonated hardness, permanent hardness, temporary hardness, calcium hardness and magnesium hardness. Different units for total hardness include: mmol/l, ppm (American degrees), mg/l, degrees of general hardness (dGH), German degrees of hardness (°dH), grains per gallon (gpg), English degrees (°e), °Clark, and °fH. I will return to total hardness later, but since CO2 depends on carbonate hardness.

Carbonate hardness (usually represented by KH, dKH, °dKH, or °dCH) is defined as the concentration of carbonate (CO3) and bicarbonate (HCO3) ions dissolved in water. The units are usually degree of carbonate hardness, dKH, similar to dGH for general hardness. Carbonate hardness is sometimes incorrectly stated to be the same as the alkalinity. The alkalinity is the level of negative ions available to neutralize the acid or H+ ions. In many cases, most of the alkalinity comes from the carbonate and bicarbonate ions. That is why carbonate hardness and alkalinity are often confused. The common test kits that measure what is called carbonate hardness are measuring alkalinity. If other types of negative ions are present, then the alkalinity can be significantly higher than the carbonate hardness. Note that the K in the KH comes from the German word for carbonate that starts with a K.

My plants did the best when I was able to get the measured KH above 3 and the GH as low as possible. I would typically end up measuring KH values that were higher than the GH measured; however, this should not be possible since KH is a single component of total hardness, GH. I still do not know why this happened, but assume it is due to the test kit measurements not accurately measuring KH and GH due to the presence of other chemicals.

If the water is too hard, the most common techniques for softening are to use reverse osmosis (RO) filtering and/or deionization with a filter cartridge containing an ion-exchange resin. Ion exchange resins are organic polymers containing anionic functional groups to which the divalent

cations (Ca++) bind more strongly than monovalent cations (Na+). When all the available Na+ ions in the resin have been replaced with calcium or magnesium ions, the resin must be re-charged by eluting the Ca2+ and Mg2+ ions using a solution of sodium chloride or sodium hydroxide, depending on the type of resin used. Reverse osmosis filters use a membrane through which the water is passed, but has pores too small for most of the minerals (calcium and magnesium compounds). The RO filters typically flush the input side of the membrane with waste water to keep the removed minerals from building up. The problems with RO filtering are that it is slow and it wastes a lot of water. Since the RO output still contains some mineral content, the RO output is often passed through an ion-exchange resin stage to remove most of the remaining mineral content. The chemicals that are desired to have in the water are then added. The total water mineral content (in ppm), called total dissolved solids (TDS), can be easily measured with a TDS meter. To increase the carbonate hardness, some form of carbonate or bicarbonate is added to the water, such as sodium bicarbonate (baking soda).

The general hardness, GH, is the measure of calcium and magnesium ion concentrations that are dissolved in water. There are other metal ions (iron, zinc, etc.) that contribute to general hardness, but they are present in relatively small amounts. The general hardness is also called the total hardness because it consists of both carbonate and non-carbonate hardness components. The carbonate hardness is also called temporary hardness because the corresponding carbonate and bicarbonate ions can be easily removed by boiling the water. When hard water is boiled in the presence of carbonate (CO3-2) or bicarbonate (HCO3-) the calcium and/or magnesium ions react with the carbonate and bicarbonate ions to form solid calcium carbonate, magnesium carbonate, or both. The term “General Hardness” is a misnomer that was really intended to be “Total Hardness.” The G in GH comes from a German word for total hardness, Gesamthärte, not General.

Much of the ground water in the United States is trickled through underground labyrinths of limestone (calcium carbonate) and has high concentrations of both calcium and carbonate. A large portion of the total hardness in this sort of water is composed of temporary hardness.

Temporary hardness is complex because its concentration is a function of the concentration of carbonates in relation to their reaction with calcium and magnesium.

Suppose your water has 100 parts per million of total hardness before boiling and 60 ppm of total hardness after boiling. This means it has 40 ppm of temporary hardness. The good thing about temporary hardness is that it is easy to remove by boiling or through precipitation with lime (calcium hydroxide). Boiling and adding lime are two of the older methods used to soften water containing temporary hardness.

Permanent hardness is simply the hardness that is not removed by boiling. If your water is gypseous, is it has passed through gypsum in the ground, then it will contain calcium and sulfate. When gypseous water is boiled, little hardness is lost, because calcium is not precipitated by sulfate.

Degree of general hardness (dGH) is a unit of water hardness, specifically of general hardness. General hardness is a measure of the concentration of divalent metal ions such as calcium and magnesium (Ca2+, Mg2+) per volume of water. In chemistry, a divalent (sometimes bivalent) ion has a valence of two. Valence is the number of chemical bonds formed. Specifically, 1 dGH is defined as 10 milligrams (mg) of calcium oxide (CaO) per liter

of water, which is equivalent to 0.17832 mmol per liter of elemental calcium and/or magnesium ions, since CaO has a molar mass of 56.0778 g/mol.

In water testing, paper strips often measure hardness in parts per million (ppm), where one part per million is defined as one milligram of calcium carbonate ($CaCO_3$) per liter of water. Consequently, 1 dGH corresponds to 17.848 ppm, since $CaCO_3$ has a molar mass of 100.0875 g/mol.

Hardness Unit Conversions

	mmol/L	ppm, mg/l	dGH, °dH	gpg	°e, °Clark	°fH
mmol/l	1	0.009991	0.1783	0.171	0.1424	0.09991
ppm, mg/l	100.1	1	17.85	17.12	14.25	10
dGH, °dH	5.608	0.05603	1	0.9591	0.7986	0.5603
gpg	5.847	0.05842	1.043	1	0.8327	0.5842
°e, °Clark	7.022	0.07016	1.252	1.201	1	0.7016
°fH	10.01	0.1	1.785	1.712	1.425	1

Example 1: 1 mmol/l = 100.1 ppm; Example 2: 1 ppm = 0.056 dGH.

The United States Geological Survey uses the following classification into hard and soft water

Classification	Hardness in mg/l or ppm	Hardness in mmol/l	Hardness in dGH/°dH	Hardness in gpg
Soft	0–60	0–0.60	0-3.37	0-3.50

Moderately hard	61–120	0.61–1.20	3.38-6.74	3.56-7.01
Hard	121–180	1.21–1.80	6.75–10.11	7.06-10.51
Very hard	≥ 181	≥ 1.81	≥ 10.12	≥ 10.57

Hardness Measurements

Water hardness is unfortunately expressed in several different units and it is often necessary to convert from one unit to another when making calculations. Most-commonly used units include: grains per gallon (gpg), parts per million (ppm), and milligrams per liter (mg/l). Grains-per-gallon is based on the old English system of weights and measures, and is based on the average weight of a dry kernel of grain (or wheat). Parts per million is a weight-to-weight ratio, where one ppm of calcium means 1 pound of calcium in 1 million pounds of water (or 1 gram of calcium in 1 million grams of water). Milligrams per liter (mg/l) are the same as ppm in the dilute solutions present in most raw and treated water (since pure water weights 1000 grams per liter).

To Convert	to	Multiply by
Grains per gallon	Milligrams per liter	17.12
Milligrams per liter	Grains per gallon	0.05841

Since calcium carbonate is one of the more common causes of hardness, total hardness is usually reported in terms of calcium carbonate concentration (mg/l as CaCO3), using either of two methods:

Calcium and Magnesium Hardness

Hardness caused by calcium is called calcium hardness, regardless of the salts associated with it. Likewise, hardness caused by magnesium is called magnesium hardness. Since calcium and magnesium are normally the only significant minerals that cause hardness, it is generally assumed that:

Total Hardness (mg/l as CaCO3) = Calcium Hardness (mg/l as CaCO3) + Magnesium Hardness (mg/l as CaCO3)

= 2.50 X Calcium conc. (mg/l as Ca2+) + 4.12 X Magnesium conc. (mg/l as Mg2+)

Carbonate and Non-carbonate Hardness

Carbonate hardness is primarily caused by the carbonate and bicarbonate salts of calcium and magnesium. Non-carbonate hardness is a measure of calcium and magnesium salts other than carbonate and bicarbonate salts (such as calcium sulfate, $CaSO_4$, or magnesium chloride, $MgCl_2$). Total hardness (which varies based on alkalinity) is expressed as the sum of carbonate hardness and non-carbonate hardness:

Total hardness	=	Carbonate hardness	+	Non-carbonate hardness
(mg/l as $CaCO_3$)		(mg/l as $CaCO_3$)		(mg/l as $CaCO_3$)

Alkalinity

Alkalinity is a measure of water's capacity to neutralize acids, and is important during softening. Alkalinity is the result of the presence of bicarbonates, carbonates, and hydroxides of calcium, magnesium, and sodium. Many of the chemicals used in water treatment, such as alum, chlorine, or lime, cause changes in alkalinity. Determining alkalinity is required when calculating chemical dosages for coagulation and water softening. Alkalinity is also used to calculate the corrosiveness of water and estimate carbonate hardness. Alkalinity (expressed as calcium carbonate $CaCO_3$) = bicarbonate ion concentration [HCO_3] + carbonate ion concentration[C03] + hydroxyl ion concentration [OH]

Carbon Dioxide (CO_2)

The carbon dioxide that is dissolved by naturally circulating waters appears in chemical analysis as bicarbonate and carbonate ions. Plants convert CO_2 to cellulose starch and related carbohydrates. These products are later reduced via respiration to carbon dioxide and water with a release of stored energy. The concentration of carbonates in natural waters is a function of dissolved carbon dioxide, temperature, pH, cations and other dissolved salts. At one atmosphere of pressure, pure C02 gas over distilled water produces a solution that would have a pH near 3.6.

Dissolved Inorganic Carbon (DIC) in freshwater occurs as four different compound types in equilibrium with one another. The four types of DIC are; carbon dioxide (CO_2), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-), and carbonate ($CO_3^=$). The total amount of DIC largely determines the buffering capacity of freshwater. The relative amounts of different DICs largely determine the pH. Carbon dioxide dissolves readily in water. At air equilibrium, the concentration of CO_2 in air and water is approximately equal at about 0.5 mg/L. Unfortunately, CO_2 diffuses about ten thousand times slower in water than in air. This problem is compounded by the relatively thick unstirred boundary layer that surrounds aquatic plant leaves. The unstirred layer in aquatic plants is a layer of still water through which gases and nutrients must diffuse to reach the plant leaf. It is about 0.5 mm thick, which is ten times thicker than in terrestrial plants. The result is that approximately 30 mg/L free CO_2 is required to saturate photosynthesis in submerged aquatic plants.

The low diffusivity of CO_2 in water, the relatively thick unstirred layer and the high CO_2 concentration needed to saturate photosynthesis limit plant growth under water.

Aquatic plants have adapted to this CO_2 limitation in several ways. They have thin, often dissected leaves. This increases the surface to volume ratio and decreases the thickness of the unstirred layer. They have extensive air channels, called aerenchyma, that allow gases to move

freely throughout the plants. This allows respired CO2 to be trapped inside the plant and in some species even allows CO2 from the sediment to diffuse into the leaves. Finally, many species of aquatic plants can photosynthesize using bicarbonate (cryptocoryne and vallisneria) as well as CO2. This is important, since at pH values between 6.4 and 10.4 the majority of DIC in freshwater exists in the form of bicarbonate.

For the aquarist, the supply of CO2 can be augmented in two ways. Both methods work by increasing the diffusion of CO2 into the plants. First, the rate of water movement in the aquarium can be increased. This will decrease the thickness of the boundary layer and ensure that CO2 levels are at air equilibrium. This method is inexpensive, easy to implement, and may produce good growth of some aquatic plants. Secondly, CO2 can be injected into the aquarium. This method can be expensive, and if done improperly, can be lethal to fish. This latter method is only essential, however, if there is a significant daily pH fluctuation in the aquarium, or if the species of plants being cultured are unable to use bicarbonate (such as Cabomba sp.).

Light

Plant chlorophyll absorbs light at wavelengths of 400 to 700 nm. This is termed Photosynthetically Active Radiation (PAR). The intensity of full, natural sunlight is approximately 2,000 umoles/m2/s, or 100 klux, of PAR. Light is attenuated rapidly in freshwater, however, so that submerged aquatic plants receive far less than this amount.

Submerged aquatic plants are adapted to the low light levels found in freshwater, and are classified as shade plants based on these adaptations. For instance, aquatic plant chloroplasts, which are the organelles that contain chlorophyll, are often located in the top cell layer of leaves to ensure that as much light as possible is absorbed. Additionally, photosynthesis is saturated at only 15 to 50% full sunlight intensity. Aquatic plants also have a low light compensation point (LCP). The LCP is the point at which the rate of photosynthesis equals the rate of respiration and growth stops. This allows them to grow to depths that receive only 1 to 4% full sunlight (20 to 80 umoles/m2/s PAR).

High light intensities are those which saturate photosynthesis. Medium intensities can be provided by 2 to 4 Watts per gallon of fluorescent lights. At this level of intensity, photosynthesis will not be at its highest level but will still be greater than respiration. Anything less than 2 Watts per gallon is low light. At this lighting level, light compensation points will be approached for many aquatic plants and only the most light-tolerant species will flourish. The attenuation of light in water is wavelength specific. Water absorbs light in the infrared and ultraviolet bands of the spectrum, organic solutes absorb blue, violet, and ultraviolet light, phytoplankton absorb blue and orange-red light, and suspended silt absorbs light uniformly at all wavelengths. Aquatic plants are therefore exposed to light that is vastly different in quality than incident radiation. Moreover, light quality underwater can change rapidly depending on water depth, turbidity, algal blooms and the level and type of organic solutes present. These data suggest that aquatic plants are flexible as to their light requirements and that the pursuit of 'full spectrum' light is unnecessary in the freshwater aquarium.

There is evidence in scientific literature that freshwater plants can sustain high growth rates under simple cool-white fluorescent light. Full spectrum lighting may be useful, however, for true color rendition, and for attempts to achieve flowering in 'difficult' aquatic plants.

Plants are sensitive to day length. The pigment that senses light in plants is called phytochrome, and it absorbs light in the red/far-red end of the spectrum. Research has shown that some aquatic plants are short-day plants, some are long-day plants, and some are indifferent to day length. When exposed to the ' wrong' day length, plants will continue to photosynthesize in the presence of light, and grow vegetatively, but will not complete their lifecycle and flower. This is true of both terrestrial and aquatic plants. Generally, it is safest to assume that tropical aquarium plants are short-day plants, which means they are more likely to flower with duration of 10 to 12 hours of light per day. Plants which grow in temperate zones are generally long-day plants and are most likely to flower with 14 to 16 hours of light per day.

Mineral Nutrients

Essential mineral nutrients are conveniently separated into two categories. Nutrients used by plants in relatively large amounts are called macronutrients. They are nitrogen (N), phosphorus (P), sulfur (S), calcium (Ca), magnesium (Mg) and potassium (K). Nutrients used by plants in small amounts are called micronutrients. They are iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), cobalt (Co), and boron (B). Other mineral elements, such as sodium (Na), are also present in plants, but there are currently no definite roles for them and so they are not classified as essential.

Aquatic plants, unlike their terrestrial counterparts, can absorb mineral nutrients both from the water through their leaves and from the sediment through their roots. Unfortunately, it is often incorrectly assumed that rooted aquatic plants can obtain all their mineral nutrient requirements through their leaves. The dramatic and superior plant growth when rooted in soil compared to plants rooted in sand has been shown for many different species and habitats.

While the better growth reasons are not completely understood, some reasons are clear. Submerged soils are lacking in oxygen. This benefits rooted aquatic plants since under anoxic conditions Fe, P and N are more available than under aerobic conditions. Nutrient concentrations are higher in fertile soil than in the overlying water. Also, there is no competition with phytoplankton for available nutrients. This is important because with water-based nutrition, too much fertilizer makes algae thrive, and too little makes plants stop growing.

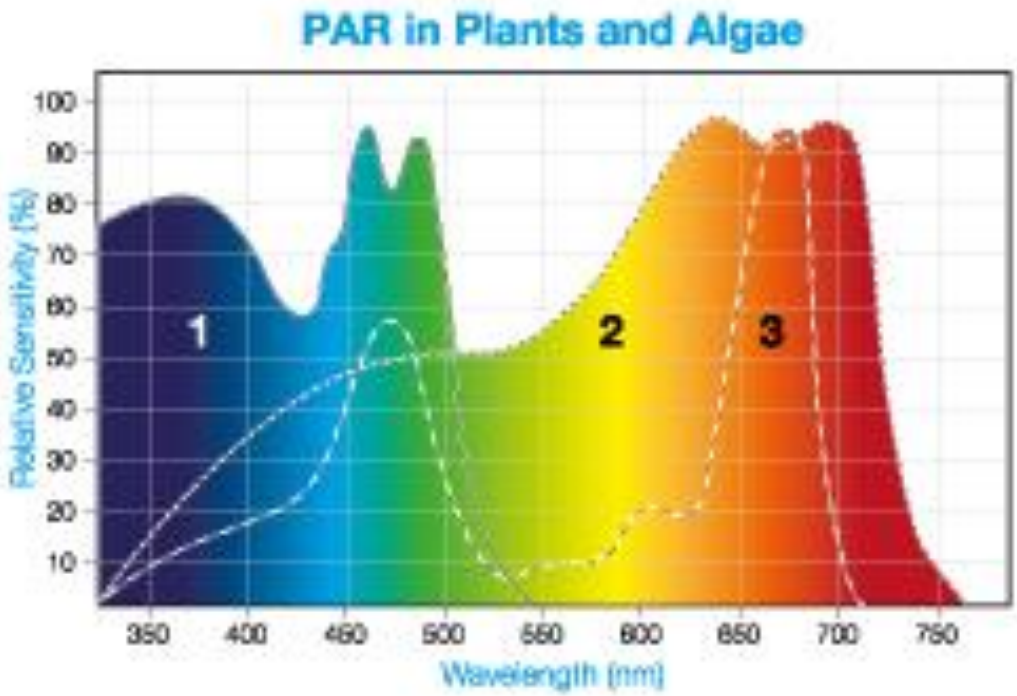
Rooted aquatic plants are well adapted to growing in an anaerobic substrate. They can get enough oxygen to the roots so that in many cases the oxygen diffuses into the surrounding sediment. They can also respire anaerobically, if necessary, and produce lactic acid or ethanol instead of CO2 as a byproduct. The root meristems (growing tips) of some species can be inhibited in the presence of oxygen.

Aquatic plants also have water nutrient requirements. Most rooted aquatic plants also need Ca, Mg, K and a carbon source in the water. Some species such as Isoetes sp. and Lobelia dortmanna can get their carbon dioxide from the sediment. These plants are adapted to growing in acidic soft water lakes that have low levels of dissolved inorganic carbon; and absorb CO2 from the sediment through their roots.

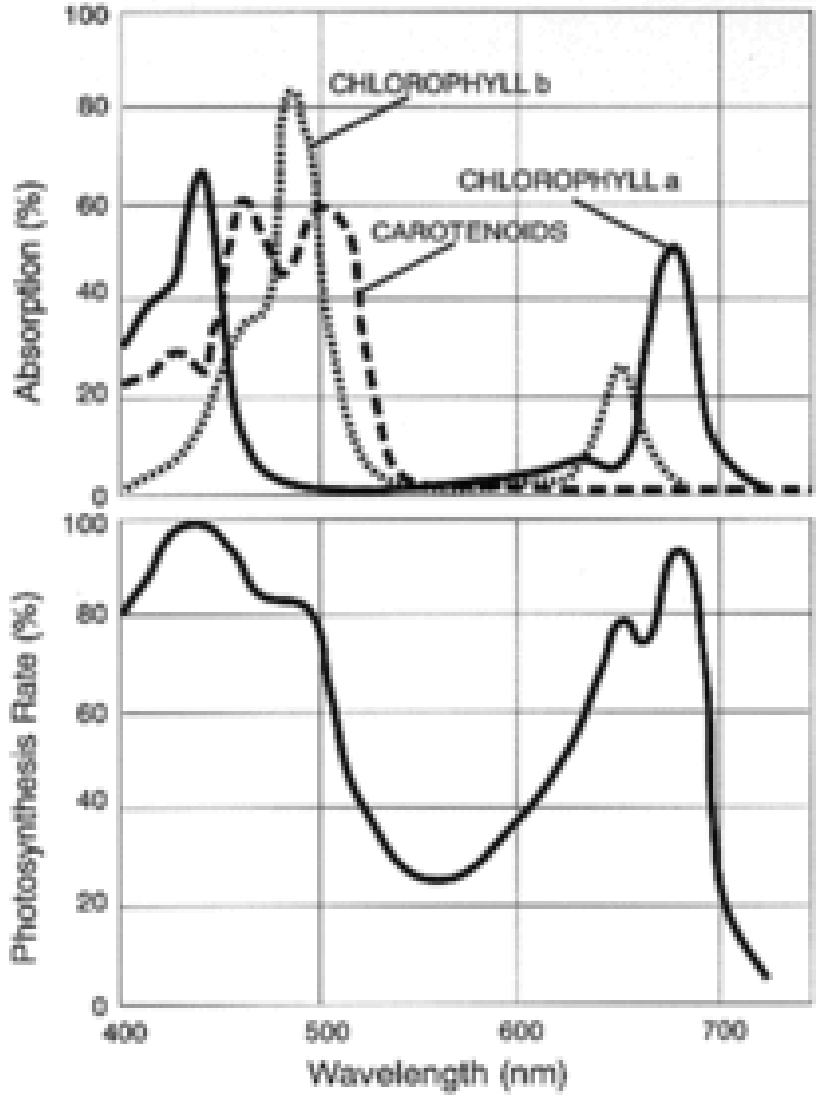
Aquatic plants grow where there are low mineral nutrients. These plants can absorb and store large quantities of nutrients for later use. Concentrations of some mineral nutrients in plants, most notably micronutrients such as Fe and Cu, can exceed the level in the water by 1,000 to 1,000,000 times. Regular additions of mineral nutrients, particularly Fe, are essential for the sustained growth of aquatic plants.

More on Light Levels

The light levels in plant profiles are based on inefficient bulb types (fluorescent). I consider moderate-high light level for compact fluorescent bulbs to be about 2-4 watts per gallon and about 0.5-1 watts per gallon for high-efficiency LEDs.



Photosynthetically active radiation, often abbreviated **PAR**, designates the spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms can use in the process of photosynthesis. This spectral region corresponds with the range of light visible to the human eye. Photons at shorter wavelengths tend to be so energetic that they can be damaging to cells and tissues, but are mostly filtered out by the ozone layer in the stratosphere. Photons at longer wavelengths do not carry enough energy to allow photosynthesis to take place.



Typical PAR action spectrum, shown beside absorption spectra for chlorophyll-A, chlorophyll-B, and carotenoids

Chlorophyll, the most abundant plant pigment, is most efficient in capturing red and blue light. Accessory pigments such as carotenes and xanthophylls harvest some green light and pass it on to the photosynthetic process, but enough of the green wavelengths are reflected to give leaves their characteristic color. An exception to the predominance of chlorophyll is autumn, when chlorophyll is degraded (because it contains N and Mg) but the accessory pigments are not (because they only contain C, H and O) and remain in the leaf producing red, yellow, and orange leaves.

PAR measurement is used in agriculture, forestry, and oceanography. One of the requirements for productive farmland is adequate PAR, so PAR is used to evaluate agricultural investment potential. PAR sensors stationed at various levels of the forest canopy measure the pattern of

PAR availability and utilization. Photosynthetic rate and related parameters can be measured non-destructively using a photosynthesis system, and these instruments measure PAR and sometimes control PAR at set intensities.

Units

PAR is normally quantified as μmol photons $m^{-2}s^{-1}$, which is a measure of the photosynthetic photon flux (area) density, or PPFD. It is sometimes expressed as Einstein units, i.e., μE $m^{-2}s^{-1}$, although this usage is nonstandard and ambiguous. PAR can also be expressed in energy units (irradiance, W/m^2); this is relevant in energy-balance considerations for photosynthetic organisms. Because photosynthesis is a quantum process, PPFD is generally used by plant biologists.

The conversion between energy-based PAR and photon-based PAR depends on the light source spectrum. The following table shows the conversion factors from watts for black-body spectra that are truncated to the range 400–700 nm. It also shows the luminous efficacy for these light sources and the fraction of a real black-body radiator that is emitted as PAR.

T (K)	**η_v (lm/W*)**	**η_photon (μmol/J* or μmol $s^{-1}W^{*-1}$)**	**η_photon (mol day^{-1} W^{*-1})**	**η_PAR (W*/W)**
3000 (warm white)	269	4.98	0.43	0.0809
4000	277	4.78	0.413	0.208
5800 (daylight)	265	4.56	0.394	0.368

Note: W* and J* indicates PAR watts and PAR joules (400–700 nm).

For example, a light source of 1000 lm at a color temperature of 5800 K would emit approximately 1000/265 = 3.8 W of PAR, which is equivalent to 3.8*4.56 = 17.3 μmol/s. For a black-body light source at 5800 K, such as the sun is approximately, a fraction 0.368 of its total emitted radiation is emitted as PAR. For artificial light sources, that usually do not have a black-body spectrum, these conversion factors are only approximate.

More on pH

pH is the negative log of hydrogen ion concentration in a water-based solution. The term "pH" was first described by Danish biochemist Søren Peter Lauritz Sørensen in 1909. pH is an abbreviation for "power of hydrogen" where "p" is short for the German word for power, potenz and H is the element symbol for hydrogen. The H is capitalized because it is standard to capitalize element symbols. The abbreviation also works in French, with pouvoir hydrogen translating as "the power of hydrogen".

Logarithmic Scale

The pH scale is a logarithmic scale that usually runs from 1 to 14. Each whole pH value below 7 (the pH of pure water) is ten times more acidic than the higher value and each whole pH value above 7 is ten times less acidic than the one below it. For example, a pH of 3 is ten times more acidic than a pH of 4 and 100 times (10 times 10) more acidic than a pH value of 5.

So, a strong acid may have a pH of 1-2, while a strong base may have a pH of 13-14. A pH near 7 is neutral. The combination of an acid with a base generally reacts to produce energy and a salt. So never directly mix a strong acid with a strong base (will explode as the water instantly boils).

Equation for pH

pH is the logarithm of the hydrogen ion concentration of an aqueous (water-based) solution:

$pH = -\log[H^+]$

log is the base 10 logarithm and [H+] is hydrogen ion concentration in the units of moles per liter.

Other Tips for Healthier Plants

Aquarium plants often do better when the substrate is warmed. In addition, there are special substrates that can be used to improve plant health. There are also special substrates designed for aquatic plants.

Appendix A. An Example Setup for Good Plant Growth and Health

In this appendix I give the setup I used to get amazing plant growth. This is accomplished by automatically injecting carbon dioxide (CO2) into the water. Other than strong light and nutrients, this is the critical component for thriving aquatic plants. Setup documentation is TBD.

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