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NITROGEN UPTAKE by AQUATIC PLANTS

By Diana Walstad (May 2017)

Ammonium and nitrite are detrimental to fish health.[1] Most hobbyists rely on filters (i.e., “biological filtration” or nitrification) to remove these toxins from the water. They do not consider using plants. Even hobbyists with planted tanks underestimate plants in terms of water purification. For they assume that plants mainly take up nitrates as their source of N (nitrogen).

However, the truth is quite different. Scientific studies have shown repeatedly that the vast majority of aquatic plants greatly prefer ammonium over nitrate. Moreover, they prefer taking it up via leaf uptake from the water, rather than root uptake from the substrate. Thus, plants can—if given the chance—play a major role in water purification. They are not just tank ornaments, aquascaping tools, or hiding places for fry.

Aquatic Plants Prefer Ammonium Over Nitrates

Many terrestrial plants like peas and tomatoes grow better using nitrates—rather than ammonium—as their N source [1]. Thus, many people, including some aquatic botanists, jumped to the conclusion that aquatic plants also prefer nitrates.

However, aquatic plants are not like terrestrial plants. Investigators determined experimentally that most aquatic plants actually prefer ammonium; only four of those studied were found to prefer nitrates (**Table 1**). Moreover, these four native species come from habitats that are severely nutrient-deprived, unlike the typical aquarium.

The ammonium preference of aquatic plants is substantial. For example, when *Elodea nuttallii* was placed in a mixture of equal parts ammonium and nitrates, the plant removed 75% of the ammonium within 16 hours while leaving the nitrates virtually

Table 1. N Preference of Aquatic Plants
(My book [3] cites the original scientific papers.)

Ammonium Preference:

- *Agrostis canina* (velvet bentgrass)
- *Amphibolis antarctica* (a seagrass)
- *Callitriche hamulata* (a water starwort)
- *Ceratophyllum demersum* (hornwort)
- *Cymodocea rotundata* (a seagrass)
- *Drepanocladus fluitans* (an aquatic moss)
- *Eichhornia crassipes* (water hyacinth)
- *Elodea densa* (Anacharis)
- *Elodea nuttallii* (Western waterweed)
- *Fontinalis antipyretica* (willow moss)
- *Halodule uninervis* (a seagrass)
- *Hydrocotyle umbellata* (marsh pennywort)
- *Juncus bulbosus* (bulbous rush)
- *Jungermannia vulcanicola* (a liverwort)
- *Landoltia punctata* (dotted duckweed)
- *Lemna gibba* (gibbous duckweed)
- *Lemna minor* (common duckweed)
- *Marchantia polymorpha* (a liverwort)
- *Myriophyllum spicatum* (Eurasian watermilfoil)
- *Pistia stratiotes* (water lettuce)
- *Potamogeton alpinus* (alpine pondweed)
- *Ranunculus fluitans* (river water crowfoot)
- *Salvinia molesta* (giant Salvinia)
- *Salvinia natans* (floating watermoss)
- *Scapania undulata* (aquatic liverwort)
- *Sphagnum* peat mosses, 8 species
- *Spirodela oligorrhiza* (a duckweed)
- *Thalassia hemprichii* (a seagrass)
- *Thalassia testudinum* (a seagrass)
- *Zostera marina* (marine eelgrass)

Nitrate preference:

- *Echinodorus ranunculoides*
- *Littorella uniflora* (shoreweed)
- *Lobelia dortmanna* (water lobelia)
- *Luronium natans* (floating water plaintain)

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1 In this article, the term ammonium automatically includes ammonia. Ammonia (NH_3) is the toxic component of ammonium (NH_4^+). At pH 7.0, an ammonium solution contains about 0.57% ammonia, but the percentage increases sharply with pH. At pH 8.0, ammonia represents 5.4% of ammonium [2].

untouched (**Fig 1**). Only when the ammonium was gone, did the plant begin to take up nitrates.

Likewise, when the giant duckweed *Spirodela oligorrhiza* was grown in nutrient media containing a mixture of ammonium and nitrate, it took up ammonium rapidly, whereas it virtually ignored the nitrates (**Fig 2**). Because the plants for this particular study were grown under sterile conditions, the ammonium removal could not have been due to nitrification. Also, the investigator showed that plants grew rapidly during the study suggesting that N uptake was due to the plant's actual use of this major nutrient.

Nitrate uptake requires light energy. For example, Water Lettuce (*Pistia stratiotes*) took up nitrates in the dark at 1/3 the rate than it did in the light. In contrast, light had no effect on ammonium uptake; plants took up ammonium at the same rate with or without light [4].

Nitrate uptake does not occur until plants are forced to use it, that is, when all ammonium is gone. Even then, there is a delay, because the setup for nitrate uptake must be generated first. Thus, Water Lettuce required 24 hours to attain its maximum rate of nitrate uptake [4].

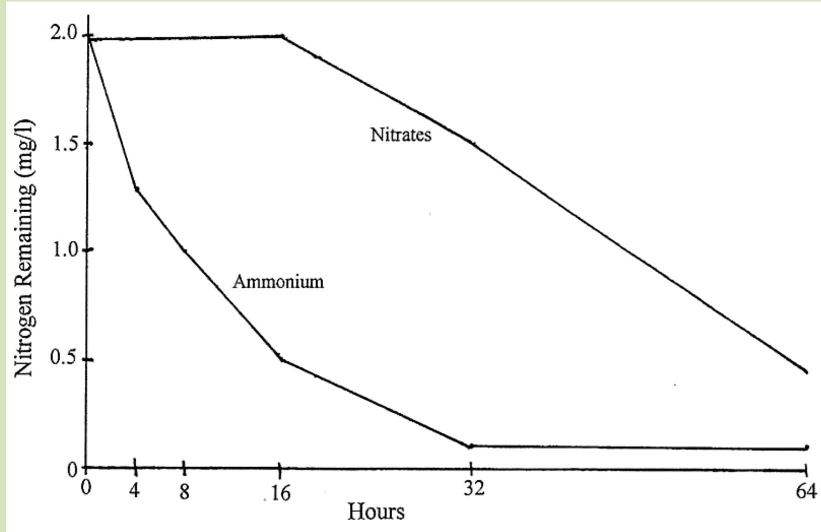

Fig 1. Nitrogen Uptake by *Elodea nuttallii* [5]

Plants (0.5 grams dry wt.) were placed in small aquaria containing 1 liter of filtered lake water plus 2 mg/l (milligrams/liter) each of NO_3-N and NH_4-N. The investigators measured ammonium and nitrate at each of the five time points—4, 8, 16, 32 and 64 hours. Each time point represents the average of 3 aquaria. [Control aquaria (no plants) showed little N loss proving that the N uptake shown here was not due to bacterial processes.]

{Figure from Ozimek redrawn and used with permission from Kluwer Academic Publishers}

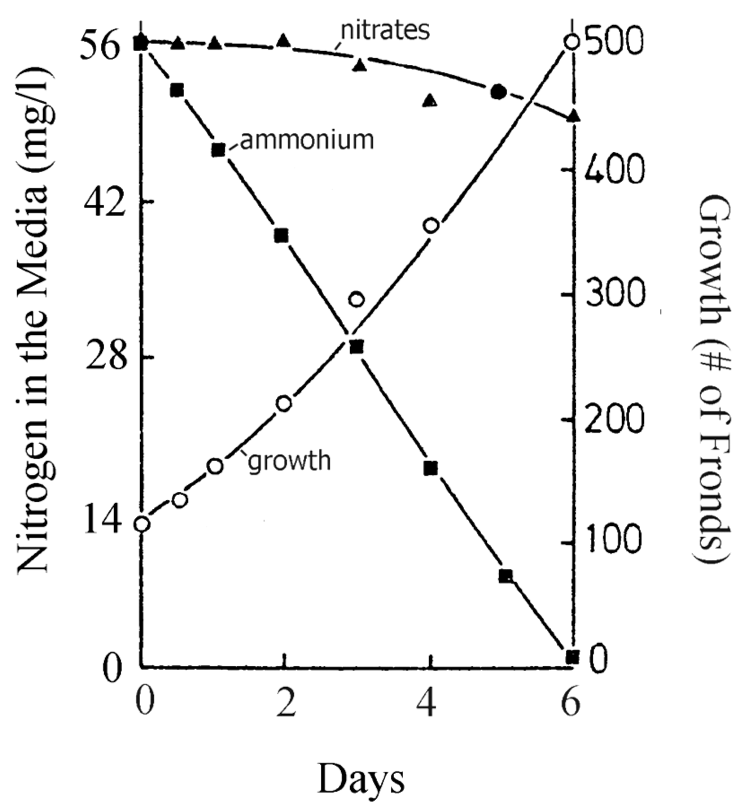

Fig 2. N Uptake by *S. oligorrhiza* [6]

Plants that had been grown with ammonium as their sole N source were transferred to media containing both ammonium and nitrate.

{Fig. 3b from Ferguson redrawn and used with permission of Springer-Verlag GmbH & Co. KG.}

Ammonium actually inhibits nitrate uptake in a variety of organisms such as plants, algae, and fungi [7]. For example, algae does not take up nitrates if the ammonium concentration is more than about 0.02 mg/l (milligrams per liter) [8]. Nitrate uptake by duckweed promptly ceased when ammonium was added to nutrient solutions [9].

Table 2 shows how much faster the Water Lettuce took up ammonium as compared to nitrate. Plants placed in nutrient solution containing 0.025 mg/l of nitrate-N, required 18 hours to take up the nitrates, but only 3.9 hours if the N was provided as ammonium. At higher N concentrations, the difference was even more dramatic. For example at 6.4 mg/l of N, nitrate uptake by plants required 44 hours, but if the N was supplied as ammonium, uptake was just 4.3 hours.

Table 2. Time Required for Nitrate v. Ammonium Uptake [4]

The investigators placed *Pistia stratiotes* in beakers with nutrient solutions containing increasing concentrations of N (nitrogen), provided as either nitrates or ammonium. Table shows the time required for the plant to take up all the N depending on concentration and type of N.

Nitrogen Concentration	Nitrate Uptake	Ammonium Uptake
0.025 mg/l	18 hours	3.9 hours
0.1	19	4.2
0.4	20	4.2
1.6	25	4.2
6.4	44	4.3

Nitrite Uptake by Plants

Although plants can use nitrite as an N source, the pertinent question for fish keepers is: Do aquatic plants remove the toxic nitrite before the non-toxic nitrate? I could not find enough studies in the scientific literature to state conclusively that they do. However, one comparison study showed that while ammonium inhibited a plant's nitrate uptake—as expected, ammonium did not inhibit nitrite uptake [10]. Theoretically, plants would need less energy to take up and use nitrite than nitrate [11]. Thus, it is not altogether unexpected that when *Spirodela oligorrhiza* was grown in media containing both nitrate and nitrite, it preferred nitrite (**Fig. 3**).

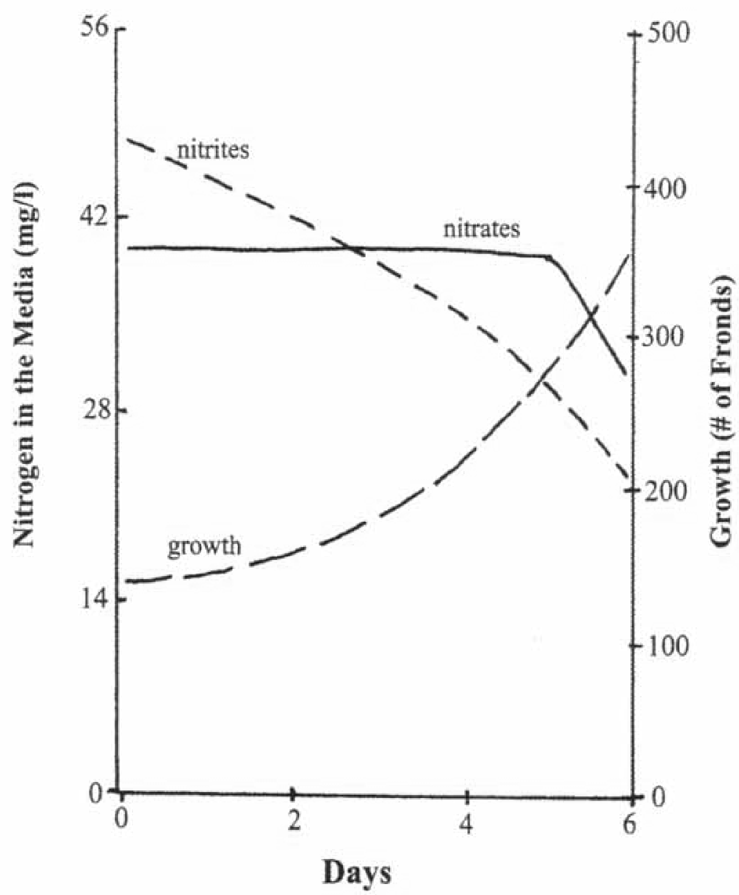

Fig 3. Nitrite Uptake by *S. oligorrhiza* [6]

Plants that had been grown with ammonium as their sole N source, were transferred to medium containing nitrite and nitrate.

{Fig. 4 from Ferguson redrawn and used with permission of Springer-Verlag GmbH & Co. KG.}

Aquatic Plants Prefer Leaf Uptake of Ammonium

If aquatic plants preferred to get ammonium by root uptake from the substrate rather than leaf uptake from the water, their ability to remove ammonium from the water and protect our aquarium fish would be lessened. Fortunately for hobbyists, aquatic plants seem to prefer leaf uptake of ammonium as opposed to sediment uptake. Thus, in split-chamber experiments with marine eelgrass [12], when ammonium was added to the leaf/stem compartment, root uptake of ammonium was reduced by 77%. However, when ammonium was added to the root compartment, leaf uptake of ammonium was not reduced.

Work with other aquatic plant species support the above findings. The seagrass *Amphibolis antarctica* takes up ammonium 5 to 38 faster by its leaves than its roots [13]. *Myriophyllum spicatum* planted in sediment containing adequate ammonium, grew fine without ammonium in the water. However, when investigators added ammonium to the water (0.1 mg/l N), plants took up more N from the water than the sediment [14].

Several aquatic plants (*Juncus bulbosus*, *Sphagnum flexuosum*, *Agrostis canina*, and *Drepanocladus fluitans*) were found to take up 71 to 82% of the ammonium from the leaves; their roots took up only a minor amount [15].

Hobbyists using fertilizer tablets for aquatic plants should understand the aquatic plant preference for leaf uptake of ammonium (as opposed to root uptake). In aquariums, fish-generated ammonium in the water can fulfill most N needs of plants. Moreover, any nitrogen added to substrates, such as in fertilizer tablets, can have bad and unintended consequences. For example, when I added nitrate-containing fertilizers to a fresh soil substrate, the fish became sick from nitrite toxicity. (Soil bacteria had converted the nitrates to toxic nitrites, which then entered the overlying water.)

Nitrification versus Plants

The nitrifying microorganisms (bacteria and archaea [16]) of biological filters gain the energy they need for their life processes solely from oxidizing ammonium to nitrates. Bacteria gain -84 Kcal/mol of energy from the two steps of nitrification. The overall reaction for nitrification is:

$$NH_4^+ + 2\,O_2 \Rightarrow NO_3^- + H_2O + 2\,H^+$$

All plants use the N from ammonium—not nitrates—to produce their amino acids and proteins. If a plant takes up nitrate, it must convert the nitrate to ammonium in an energy-requiring process called ‘nitrate reduction.’ Plants must expend essentially the same amount of energy (83 Kcal/mol) that the nitrifying bacteria gained in order to convert nitrates **back** to ammonium. The overall reaction for the two-step process of nitrate reduction in plants is:

$$NO_3^- + H_2O + 2\,H^+ \Rightarrow NH_4^+ + 2\,O_2$$

The energy required for plants to reduce nitrates to ammonium is substantial, equivalent to 23% of the energy obtained from glucose metabolism [1]. Thus, if nitrifying bacteria convert all available ammonium to nitrates, plants will be forced—at an energy cost—to convert all the nitrates back to ammonium. This may explain why investigators have shown that several aquatic plant species grow better with ammonium (or a mixture of ammonium and nitrates) than with pure nitrates [3].

The nitrogen cycle is often represented incorrectly to aquarium hobbyists as nitrifying bacteria converting ammonium to nitrates, and then plants taking up nitrates. Actually, it consists of both plants and microorganisms competing for ammonium. Plants will only take up nitrates when they are forced to. Thus, nitrates may accumulate in aquariums, even those with good plant growth.

Biological filtration can cause problems in aquariums, for the nitrification reaction (*See* above) generates acidity and consumes oxygen. Every ammonium converted to nitrate automatically consumes two oxygen molecules (O_2) and generates two acids (H^+). In tanks that I maintained earlier with no plants (or which had poor plant growth), the water often became quite acidic. Once I promoted good plant growth in my tanks, I never had a tank "go acid."

In unplanted tanks, biological filtration is essential for protecting fish from ammonium. However, it is not essential in planted tanks. I have been surprised by how little filtration is required in my planted aquaria. When I removed the internal media from canister filters, the fish did fine. When I removed the filters altogether and just used internal pumps to circulate the water, the fish did fine. I concluded that biological filtration was totally unnecessary in my planted tanks.

Aquatic plants quickly remove ammonium from the water. That is because aquatic plants vastly prefer ammonium over nitrates as their N source. Furthermore, they remove it within hours, both night and day. Plants benefit fish in many ways—produce oxygen, purify the substrate, consume CO_2, and stabilize the pH. However, rapid ammonium removal—without nitrification's deleterious side effects—is a major benefit, one that has long been underestimated by aquarium hobbyists. I hope this article provides one very good reason for keeping plants in fish tanks.

Plants as the "Biological Filter"

The fish in this 50 gal tank do well despite minimal filtration and water changes. The internal filter shown on the right mainly circulates the water. I depend on good plant growth rather than nitrification to protect my fish from ammonia and nitrite.

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Much of this article was excerpted from *Ecology of the Planted Aquarium* [3].
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