Aquaponics Simplified 簡化的複合養殖

by: Steven Carruthers

翻譯：方煒

WILSON LENNARD outlines his research to develop a successful recirculating aquaponic system to produce Murray Cod and lettuce, with significant savings in water use and zero environmental impacts.

威爾森尼歐納介紹他研究成功的可節約大量用水且對環境沒有影響的循環水鱈魚養殖與萵苣栽培的複合系統。

I came to the world of aquaponics from the otherside , that is, the aquaculture side. Freshwater aquaculture is moving into a new phase and a lot of people are now turning towards using large, environmentally controlled indoor recirculation systems to grow fish. These systems are a self-contained unit, usually located in an insulated shed. These are high intensity systems, with tons of fish being produced annually on very small land areas. The advantage of recirculating fish farming is that water is recycled through the system, and is therefore used to its full advantage.

我是由養殖端進入複合養殖領域的，我原本從事養殖。目前有許多新人加入在室內、以循環水系統從事大規模的淡水魚類的養殖。這類系統通常於密閉的室內，採高密度(集約)方式進行，每年有數以噸計的魚類被飼養於相對頗小的土地面積。這循環水養殖系統的優點就在於水體被充分地循環使用。

The downfall of any aquaculture operation is that fish produce waste, and this waste needs to be disposed of in a way that won't impact on the environment. Fish waste is nutrient rich and if it is disposed directly to the environment, it can have negative consequences. This is where aquaponics and I come into it.

任何養殖系統都需要面對魚類的廢棄物，而此些廢棄物必須被處理才不至於對環境造成影響。魚類的廢棄物其實是富於營養的，如果直接排放於環境中將對環境不利，所以複合養殖應運而生，我也自然走入這個領域。

I was looking for a way to filter the nutrient-rich fish waste out of aquaculture systems. Solid fish waste is constantly removed from these systems and is usually composted, so it is not much of a problem. It is the water-bound fish waste that is a problem.

我在找尋可以去除水中富於營養的魚類廢棄物的方法，固形物的去除為例行作業，通常拿去做堆肥，不會有太大困擾，但是

對於那些溶於水中的廢棄物才讓我頭大。

Around 70% of fish waste is actually water-bound, arising from the gas exchange of ammonia-type waste that the fish excrete across their gills. It is this water-bound component that I was looking to treat. So, from my point of view, I was looking for a way to remove water-bound waste from our fish culturing systems. This is required because fish farmers at present change approximately 10% of their water every day, to counteract this build-up of waste. Ten percent may not sound like much, but in a system containing 100,000 litres of water (which is not a large system), that means removing 10,000L of water a day, finding a way to dispose of it, and replacing it with 10,000L of clean, fresh water. So, as I said, I was coming at the problem from a fish culturalist perspective.

大約有 70%的魚類廢棄物為水溶性，來自於魚類透過鰓做氣體交換所排出的氨態廢棄物，這是我想處理的。我想找一個方法可以去除我養殖系統中的這類廢棄物。這是必要的，因為目前的循環水養殖業者每天更換 10%的養殖水來解決這個問題，這數字看來不大，但是對一個有 100 噸水體(規模不大)的養殖事業，代表每天要排放 10 噸的水並找新鮮水進來，排放水還有環保法規需遵守。如我前面所說，我是從養殖者的角度切入的。

The great thing about this water-bound fish waste is that it is mainly nitrates and phosphates. As all hydroponic plant growers know, these are some of the main nutrients used for hydroponic plant culture. So the question arose, can these fish wastes be used as plant nutrients? This is where I started after obtaining a PhD scholarship through the Rural Industry Research and Development Corporation (RIRDC).

養殖水中的可溶性廢棄物飽含氮與磷，這些是水耕栽培作物需要的大量元素，所以這些營養能否被植物吸收呢？在我拿到 RIRDC 給我的博士研究獎助學金之後，針對這些問題開始研究。

I set about designing and building an aquaponic system to integrate fish culture with hydroponic plant culture. I had to design a very small-scale system, as I needed to be able to replicate my experimental situations for scientific purposes. So I eventually ended up with 12 aquaponic units that were identical to each other.

我開始設計並建立複合養殖系統來整合水產養殖與水耕的系統，為了科學研究的理由，在需要有足夠的重複試驗的樣本狀況下，我由小的系統做起，最後做了 12 組完全相同的複合養殖系統。

A unit consists of a 100L fish tank with an associated biofilter. The biofilter is very important to the fish's health, as it converts harmful ammonia released by the fish into harmless nitrate. Above the fish tank is a shelf containing a hydroponic gravel bed. Water can be pumped from the fish tank, up to the hydroponic gravel bed, and then returns to the fish tank. That's it. It's pretty basic, but it really works.

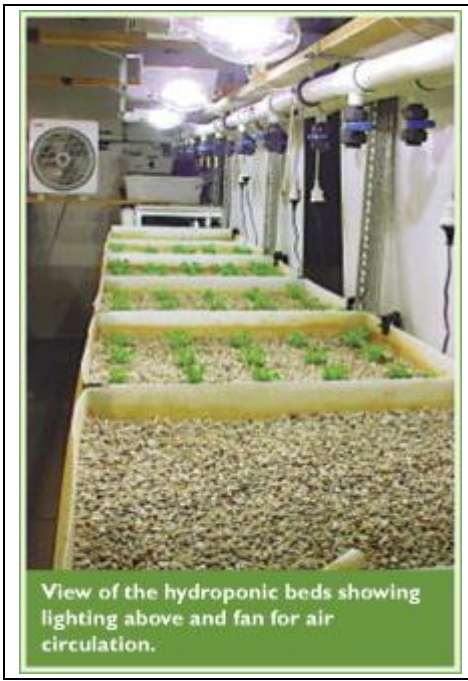
每一組有 100 公升的養殖魚槽搭配生物濾床，後者在養殖上非常重要，主要功能在將有害的氨態氮轉換為無害的硝酸態氮。養殖魚槽上方為水耕的栽培礫石植床，循環水用馬達由水槽打上植床，通過礫石回到水槽。既簡單又有效。

AQUAPONICS THEORY 複合養殖的原理

The theory behind aquaponics is this: the fish live in a tank, eat fish food, and produce two types of waste; solid waste (fish poo) and water-bound waste. As I said earlier, solid waste is routinely removed and generally

composted. The water-bound fish waste is actually the same nitrate and phosphate hydroponic farmers add to their systems using inorganic salts that they purchase.

魚在養殖槽內生存，產生兩種型態的廢棄物：固態(排泄物)與水溶性。如前所言，前者多半透過定期的收集製造堆肥，後者基本上所含的氮與磷與水耕栽培業者使用無機鹽類調配的營養液的成分是相同的。



View of the hydroponic beds showing lighting above and fan for air circulation.

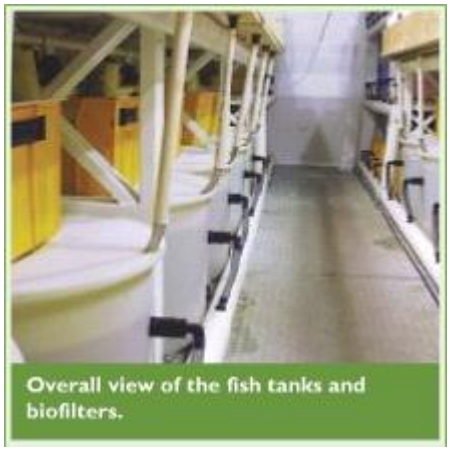
照片顯示水耕植床上方的燈光與風扇
提供室內空氣循環

What was fish waste, is now plant nutrient. The water from the fish tank is pumped to a hydroponic plant culturing component and the nitrate and phosphate from the fish is used to feed the plants. The water, now 'cleaned' of nutrients, is then returned to the fish tank and the whole cycle begins again.

魚類廢棄物現在就成了植物的營養，養殖槽中的水體被輸送到水耕栽培的植床，氮與磷被植物吸收，乾淨的水體回到養殖槽，完成一個循環。

If the amount of waste the fish produce can be balanced with the amount of nutrient the plants require, then we should have a system where we can perpetually grow fish and plants in the same water, with no water replacement required, other than that used to replace transpiration from the plants.

如果魚類廢棄物與植物所需要的營養能夠維持供需量的平衡，基本上我們就有一個使用同一套水體就能持續養魚與栽培植物的系統，除了補充蒸散失去的水分之外不需補充其他的水。

 Overall view of the fish tanks and biofilters.	魚槽與生物濾床的全貌

So I set about running a number of experiments to develop the idea within an Australian context. Some of the questions that arose were:

所以我設計一系列實驗來回答一些合乎澳洲規範之內的想法，其中的一些想法/問題簡列如下：

- does this aquaponics thing really work? 這種複合養殖系統真的能用嗎？
- can Australian fish species be used? 能否養殖澳洲的本土性魚種？
- what pumping rates are required? 需要多大的流量？
- what hydroponic systems can be used (gravel bed, floating raft, NFT etc…)? 那一種水耕系統比較適合(礫石床、浮板，或是養液薄膜法)？
- are there any nutrient deficiencies in the plants? 植物的營養是否會缺乏某幾樣？
- is the system productive in a commercial sense? 這類系統是否可商品化？

The question of does the aquaponic process actually work was answered with my first experiment. One kilogram of fish was placed in the tanks and 20 lettuce seedlings planted. The fish were fed, the system monitored and the fingers crossed. It is an amazing thing to inspect an aquaponic system daily and watch both the fish and plants grow and thrive. After three weeks in the aquaponic system, I had harvest size lettuce (around 120g, Green Oak fancy heads), fish that had grown, and water with 80% less nutrient in it than the fish-only controls.

第一個問題在我第一次實驗就獲得了答案了。養殖槽中放入 1 公斤的魚，搭配 20 株的萵苣種苗。魚類定期餵飼，系統監測中，期望一切順利。複合養殖系統允許每天觀察魚與植物，看著他們的成長真是美好的事。三週後，我收穫了 120 g 的萵苣(俗名：Green Oak Fancy Heads 綠橡木美結球)，魚也成長了，比起沒有植物搭配的養殖對照組，水中的營養鹽更是少了 80%。

This was definitely a good way to start for a PhD student -success! The fish were healthy and had grown at a rate the same as the industry standard, with no side effects. In fact, they actually seemed to like their new, cleaner environment. The lettuce plants were full of head and a beautiful, rich green, with no signs of nutrient deficiency.

我的博士研究看來會成功了，於看來很健康，成長速率與一般工業化養殖沒甚麼兩樣，也沒有不良的副作用。事實上它們似乎更喜歡這樣經常維持水體乾淨的環境。萵苣成長看來也頗健康，深綠色，看不出缺甚麼營養。

At this point I was wondering, is there really three years of research in this? What followed was two and a half years of further experiments and trials to try and optimise the system for better plant growth and better nutrient stripping from the system.

到此我不禁思考，三年的研究期間就只要做這些嗎？我還有兩年半，是否多做些試驗，嘗試將系統最佳化讓植物長的更好，水中廢棄物也去除的更乾淨。

WHERE ARE WE AT THEN? 目前我們在甚麼狀況？

Well, we now have a system that is fully optimised and is ready for commercial trials. Some of the variables that you may be interested in include: gravel beds work better on a constant flow water delivery regime.

好了，我們目前有一個幾乎可以商品化的系統。有些參數或許你會有興趣，譬如：礫石植床最適合搭配連續的循環水系統。

Top: Lettuce at 3 days after planting.
Above: Overall view of the replicated aquaponic systems.

移植後第三天的萵苣

多組重複的複合養殖系統的全貌

Past hydroponic research has suggested that a 'reciprocal flow' (water is pumped to the gravel bed now and then, instead of a constant flow) was better as it aided water oxygen levels and distributed nutrient to plants better. This may be true in standard hydroponics, but we always require oxygen above 5mg/L for our fish, so oxygen is always above what the plant roots require (around 2mg/L for lettuce).

過去水耕的研究建議應採間歇供水的方式而非連續流的方式，因為可以幫助在水體內加入氧氣，並將養液輸送至植物。這在傳統的水耕方式或許是正確的，但是以養殖來說，魚體需要的溶氧量至少要 5 mg/L，對植物(萵苣 2 mg/L)來說是充分足夠的。

Our constant flow gravel bed system grows lettuce about 20% better than a reciprocal flow. Gravel beds and floating rafts are about 15-20% more efficient than NFT. My experiments have proven, within an aquaponic context, that NFT is less efficient at plant growth and nutrient stripping.
我們採用連續流礫石植床種的萵苣的產能比間歇灌溉的系統高出 20%，礫石植床與浮板與 NFT 高出 15-20%的效率。我的實驗證明，NFT 在複合養殖系統中，不論由植物栽培或可溶性廢棄物去除效率來說都是比較沒有效率的。

The last key finding is that we need to use a potassium and calcium-based buffer system. Fish farmers use sodium bicarbonate and similar basic salts to make sure the pH doesn't drop. Fish systems are the opposite to hydroponic systems - as fish eat and metabolise feed, the water pH drops.
最後一個重要的發現是我們**需要使用以磷和鈣為主的緩衝系統**，養魚者使用碳酸氫鈉或類似的基礎鹽類來確保水體的酸鹼度不會下降。養魚的系統與水耕系統正好相反，當魚吃進飼料並進行新陳代謝之後，水體會變酸。

To counteract this pH drop, we use buffers to keep the pH up around 7. If we use potassium and calcium-based buffers, we can add the potassium and calcium to the system that the plants require for good growth.
為了抵銷水體變酸，需要使用緩衝溶液來維持水體的 pH 接近 7。如果我們用磷與鈣為基底的緩衝溶液，磷與鈣都可被植物利用來維持好的生長。

KEY RESEARCH FINDINGS

So I had better tell you of the key findings. Fish (we used Murray Cod) and plants (we used lettuce) can be grown in an integrated aquaponic system. If the correct balance is met between plants and fish, no nutrient build-up occurs in the system, and the plants get all the nutrients they need.
關鍵的其他資料如下：養殖物種，我們養的是鱈魚，植物則是萵苣，兩者可以整合在複合養殖系統內。當植物與養殖物達到正確的平衡，系統中的營養成分不會累積，植物也可得到所需的所有養分。

We don't get conductivity build-up or drop-off; it stays constantly at about 500mS/cm. This is because the fish renew the nutrients every time they are fed, which can be as high as 3-4 times per day, and the plants constantly use those nutrients.
水體的導電度不會累積也不會下降，維持著 500 mS/cm。這是由於魚每天餵 3 至 4 次，廢棄物不斷產生，就有足夠營養可不斷提供給植物。

A combination of potassium and calcium is used to buffer pH and provide the other essential plant nutrients. We also add a little chelated iron, as fish food is lacking in iron and the plants require it to produce chlorophyll. That is all we add to the system - fish food, a little buffer each day, and a little iron once a week. All the micronutrients required for the plants are in the fish food, so we don't need to add any of these.
磷與鈣的組合用來提供 pH 的緩衝並供應其他植物需要的必要元素。我們也添加一些螯合鐵，因為飼料中缺乏鐵元素，而這

是植物葉綠體的必要成分。整個系統中，我們就是每天加入魚的飼料與一點緩衝液，每週加入一點螯合鐵。植物需要的所有微量元素在飼料中都包括了，所以不需添加其他的成分。

 Top: View of the fish tank (with fish) and biofilter of an experimental aquaponic test unit. Above: showing fish, fish hides (100mm PVC pipe), submersible water pump (for water delivery to hydroponic bed), and outflow from the biofilter.	一組複合養殖系統的魚槽（有魚)與生物濾床 顯示魚，被魚擋住的 100 mm PVC 水管，沈水馬達（輸送水至植床）與由生物濾床流回來的水

WHAT ARE THE ADVANTAGES OF AQUAPONICS? 複合養殖系統的優點

There are several advantages; some relate to the fish and some the plants. Because we can balance the nutrient output of the fish with the nutrient uptake of the plants, we never need to exchange water. We do need to replace any water lost through plant transpiration, but this is a small amount. We are now saving above 90% of the water a normal recirculating fish farm would use. So, the system is very water friendly. We have no nutrient-rich waste output, we use our nutrients to feed the plants, and we have zero environmental impact.

應有好幾樣優點，一些與魚有關一些與植物有關。由於我們能夠平衡魚與植物對養分供需狀態，我們不需要換水，補充蒸散之消耗所做的補水量是很少的。我們可以節省超過 90%的循環水的水量，所以用水非常環保，對環境的影響也最小，因為富含養分的廢水都沒有流失。

Our fish grow just as well as they do in any other fish system. The best outcome is that we grow healthy, strong plants that yield at the same rate as they would in standard hydroponics. That's right, our lettuce grew just as well in our aquaponic system as they did in our hydroponic controls. So, the advantages are:

我們的魚長的和其他養殖系統一樣好，更好的是我們同時栽培了與其他水耕系統一樣品質的萵苣。所以，優點就是：

- excellent fish and plant growth　非常優良的魚與植物的生長
- zero environmental impact　對環境無危害
- efficient water use　高效率的水體利用
- yields as good as the prospective stand-alone industries, and 產能與單獨的系統一樣
- the ability to grow two cash crops (fish and plants) off the one food source. 同時生產兩樣產品而只使用一種飼料

I am now building a commercial-scale aquaponic system. We will have the ability to grow around 500kg of fish a year and harvest 3,000 lettuce per week. We will have no environmental impact and will use less than 10% of the water a normal recirculating fish farm would use. The only other question is whether we can obtain "Organic" certification? If we can achieve this, we believe we are on a definite winner. But more about that in a coming issue.

我現在正在建一種商業化的複合養殖系統，將來可以年產 500 公斤的魚且每週可收穫 3000 顆萵苣。同時對環境不會影響且只會使用少於傳統循環水養殖系統用水量的 10%。唯一的問題是不知道我們這種養殖模式可否拿到有機栽培的認證？如果可以，那麼這鐵定是一個成功的商業模式。下一期我將多介紹這方面的進展。(註 by 方：這種系統在台灣目前不被認定為有機)

***About the Author* 有關作者**

Wilson Lennard is in the final stages of his research into aquaponics at RMIT University, Melbourne, Australia. He believes aquaponics is a new and emerging industry that will fill a defined niche in the aquaculture/hydroponics market.

威爾森尼歐納目前正在澳洲墨爾本 RMIT 大學進行複合養殖最後階段的研究，他相信整合養殖與水耕栽培的複合養殖會是一個可以蓬勃發展的新產業。