行政院國家科學委員會專題研究計畫　成果報告

利用人工溼地技術管理水產養殖場水及廢水之研究

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計畫主持人：林瑩峰
共同主持人：荊樹人，李得元
計畫參與人員：蘇瑢煋

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中　華　民　國 94 年 10 月 3 日

行政院國家科學委員會補助專題研究計畫

☑ 成 果 報 告
□期中進度報告

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成果報告類型(依經費核定清單規定繳交)：☑精簡報告　□完整報告

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執行單位：嘉南藥理科技大學環境工程與科學系

中　華　民　國　94　年　09　月　30　日

中文摘要

本研究將人工溼地技術應用到魚塭循環水養殖中，利用溼地的自然淨水能力作為養殖廢水的淨化及管理單元，以維護魚塭養殖池水水質及降低養殖場排廢水的污染。本文主要探討了人工溼地對養殖水中主要汙染物的處理效能，及人工溼地的淨化能力對維持魚溫水質的影響。人工溼地是利用既有的漁塭整地後改造完成（$105m^2$），由一個表面流動式（FWS，free water surface flow system）溼地與另一個表面下流動（SSF，subsurface flow system）溼地所組成，此人工溼地並與一個魚塭（$1125m^2$）以管線及幫浦建構成循環水養殖系統；另外，設置一個無循環水處理的魚塭（$1138m^2$）作為傳統魚溫養殖水質比較的控制組；兩處魚塭均飼養白蝦(*Litopenaeus vannamei*)。本研究進行了兩個試程的養殖及水質淨化試驗，第一試程自 93 年 7 中旬至 9 月中旬，第二試程自 93 年 12 月中旬至 94 年 5 月底。由水質監測結果得知，魚塭循環水經人工溼地處理後出流水均維持相當良好的水質，由進流水—出流水水質評估，第一試程及第二試期間人工溼地對 BOD_5 的去除效率分別為 47.3 及 58.2%，對 SS 的去除效率分別為 70.8 及 68%，對濁度的削減效率分別為 60.9 及 59.7%，及對葉綠素 a 的去除效率分別為 50.9 及 51.9%。比較循環水養殖魚塭與控制組漁塭的水質分析結果，第二試程期間 SS 濃度為分別為 25 ± 12 與 58 ± 39 mg/L，BOD_5 分別為 6.2 ± 3.0 與 10.5 ± 2.6 mg/L，濁度分別為 16.47 ± 6.07 和 29.84 ± 10.20 NTU，及葉綠素 a 分別為 16. 9 ± 11.4 和 50.3 ± 50.8μg/L。循環水養殖魚塭的水質顯著的($p<0.05$)優於控制組漁塭的水質，本研究結果顯示人工溼地可作為傳統魚塭養殖專為水質控制及管理上低成本之生態工法。

關鍵字: 人工濕地、循環水養殖

Abstract

This study is to integrate constructed wetland, or treatment wetland, technology into the recirculating aquaculture, in which constructed wetland is used as a facility for aquaculture water treatment so as to control the water quality in fishpond and reduce pollutant level in the fishpond discharge. The constructed wetland ($105m^2$) was built using part of an existing fishpond, and included a free water surface flow unit followed by a subsurface flow unit. A fishpond ($1125m^2$) was connected with the treatment wetland to constitute a recirculating aquaculture system. Another fishpond ($1138m^2$) without connection of treatment wetland was used as a control fishpond, in which traditional static aquaculture was carried out. This study investigated the performance of the constructed wetland in removing the major pollutants from the recirculating aquaculture water, and examined the effect of wetland treatment on water quality of the fishpond in the recirculating aquaculture system. Two aquaculture trials stocked with larvas of Pacific white shrimp was conducted. One trial was carried out from the middle July to the late September, 2004; another trial was started from the middle December, 2003 to the late May, 2005. Results of water monitoring of influent-effluent showed that constructed wetland effectively reduced BOD5 (47.3~58.2%), TSS (68~70.8%), turbidity (59.7~60.9%), and chlorophyll a (50.9~51.9%) from the recirculating aquaculture water. Water quality of recirculating fishpond were maintained at 25 ± 12 and 58 ± 39 mg/L for TSS，6.2 ± 3.0 and 10.5 ± 2.6 mg/L for BOD_5，16.47 ± 6.07 and 29.84 ± 10.20 NTU for turbidity，and 16. 9 ± 11.4 and 50.3 ± 50.8μg/L for chlorophyll a in trials 1 and 2, respectively. These levels of pollutants were significantly lower ($p<0.05$) than those in the control fishpond. Constructed wetland was demonstrated to be an efficient and low-cost ecological approach to management water quality and control pollution discharge in a fish farm.

Keyword: constructed wetland, recirculating aquaculture

一、前言

台灣地區水產養殖業蓬勃發展，沿海鹹水、半鹹水養殖及內陸淡水養殖業相當盛行，水產養殖產業帶動了農、漁村的經濟發展。然而，傳統魚塭養殖方式養殖面積需求大、用水量大，當養殖池水質惡化時，須排放池水、更換新水，因而產生大量的污染性排廢水，增加水體污染負荷，導致水體優養化及缺氧並進一步破壞水體生態。另外，可作為養殖水源之地面水體普遍受到污染，養殖業於是多採用地下水為主要水源，因此可能導致超抽地下水及引發不少地區（特別是沿海地區）地層下陷的環境衝擊(1)。

根據文獻(2)報導養蝦場從事每批次養殖對水體之總污染物負荷量約為總磷 321 kg/ha、總氮 668 kg/ha、總懸浮固體物 215,000 kg/ha。而養殖彩虹鱒魚(rainbow trout)每年獲量 25000 ton 的養殖場，估計由排廢水中產生 1300 ton 的總氮及 150 ton 總磷的污染負荷(3)。根據國內研究報導，曾針對台南縣仁德鄉二行村境內某養殖業者之虱目魚白蝦混養之漁塭，進行其魚塭排廢水之採樣分析，調查結果如下：COD 100~156 mg/l，總氨氮 0.16~3.31 mg/l，亞硝酸氮 0.03~1.6 mg/l，硝酸氮 0.2~2.6 mg/l，溶解性磷酸鹽 2.4~10.5 mg P/l，懸浮固體物(SS) 70~159 mg/l，pH 7.7~8.5，葉綠素 a 76~117 μg/l(4)。養殖過程中因養殖物所產生的排泄物與分泌物、加上飼料之殘餘，在養殖過程中會累積於池內，因而造成池水水質惡化，顯見水產養殖場排廢水的污染性。

循環水養殖技術（recirculating technique），是利用一水質淨化系統處理養殖池水，以去除養殖物所產生之代謝物質及餌料殘餘，處理水並循環回流至養殖池。此方式可使養殖池水維持於良好水質，養殖物有良好的生長環境，病害發生率可望降低，生長率亦可能提高，因而提升養殖產品品質，並可進行高密度的養殖(intensive aquaculture)(5-6)。此外，可減少換水需求，降低用水量及排水量，減輕地下水超抽及水產養殖業廢水污染之問題。除了上述優點外，以循環淨水單元來控制養殖池的水質，亦可一併淨化排廢水，使養殖業的廢水污染負荷獲得減輕，實為台灣養殖業永續發展的重要途徑。

一般循環水養殖系統主要的水處理流程為：過篩、沉降、砂濾、生物處理單元、曝氣、消毒。但是這些處理單元基本上是屬於機械式處理法、需求能源、須經常且專業性地操作維護、易造成二次污染等問題，並且初設置成本昂貴。另一方面，人工濕地系統（constructed wetland system）為一種省能源、低成本、無二次污染、操作維護簡單、不破壞生態的綠色環保技術(7)。人工濕地系統是將生態工程技術應用於水或廢水管理及處理上的一種自然淨化程序，具有可將污染物同化及轉換的能力（兼具物理、化學及生物處理特性）、不需能源輸入及不必經常維護便可自給自足等優點。國外的研究報導已證實人工溼地可適合於水產養殖排廢水的處理，經有效處理後可讓排廢水符合放流水標準。

目前，所發展出來的人工濕地系統有兩種類型(9)。其一，稱為自由水層系統（FWS，free water surface flow system），高密度地種植挺水性水生植物（如燈心草、薹草、蘆葦、香蒲等）；進流水則在濕地表層開放性地流動，當水流經植物的莖及根部可行淨化作用。另一種系統，稱為表層下流動系統（SSF，subsurface flow system），進流水被迫在表層下的砂土間流動，以達到淨化作用；此種系統則是在歐洲、澳洲及南非較盛行。綜覽文獻，提出人工濕地可作為水產養殖場排廢水處理及回收再利用的重要技術方法(10)。美國亦曾利用 FWS 型溼地處理鯰魚(catfish)漁塭之排廢水，在水力停留時間(HRT)1~4 day 的操作範圍下，獲得良好的處理效果：BOD_5 37-67 %、SS 75-87%、氨氮 1-81%、亞硝酸氮 43-98%、硝酸氮 51-75%、TP 59-84%(11)。還有本人工溼地團隊陸續證實人工溼地在養殖業水及廢水處理與管理上之應用潛力(12-17)。

二、研究目的

本研究將人工溼地技術應用到魚塭循環水養殖中，利用溼地的自然淨水能力作為養殖廢水的淨化及管理單元，以維護魚塭養殖池水水質及降低養殖場排廢水的污染。本文主要探討了人工溼地對養殖水中主要汙染物的處理效能，及人工溼地的淨化能力對維持魚塭水質的影響。

三、文獻探討

綜覽文獻[18-23]，將人工濕地應用於水產養殖廢水之處理及再利用之國內外研究報導並不多。然而，由養殖排廢水中的主要污染物（包括：有機物、懸浮固體、CO_2、含氮物質、含磷物質、病原菌等）觀之，人工濕地的能力應是游刃有餘。

Zachritz and Jacquez (1993)[18]首先提出人工濕地可作為水產養殖場排廢水處理及回收再利用的重要技術方法。

美國 Schwartz and Boyd(1995)[19]曾利用 FWS 型溼地(長 84 m×寬 14 m×兩座)處理鯰魚(catfish)漁塭之排廢水，在水力停留時間(HRT)1~4 day 的操作範圍下，獲得良好的處理效果：BOD_5 37-67 %、SS 75-87%、氨氮 1-81%、亞硝酸氮 43-98%、硝酸氮 51-75%、TP 59-84%。

泰國 Sananayuth et al(1996)[20]亦曾利用小規模 SSF 溼地(長 13 m×寬 1.2 m)種植耐鹽性的紅樹林植物(mangrove fern)，處理養蝦漁塭的排廢水，在 HRT 為 1~3 天條件下操作，對污染物的去除效率可達：BOD_5 91 %、SS 84%、TN 48%、TP 31%。

美國 Summerfelt et al. (1999)[21]亦報導利用小型 SSF 型溼地(長 3.7 m×寬 1.2 m)作為污泥脫水曬乾床，處理養殖場因固液分離設備所產生的濃縮污泥(固體含量約 7500 mg/L)，並證實污泥流經 SSF 溼地後具有脫水及穩定化的作用。

美國 Tilley et al. (2002)[22]曾使用一個 7.7 公頃的 FWS 人工濕地在平均水力負荷 0.177 m/day 的操作條件, 處理來自一個 8.1 公頃養蝦漁塭所產生的排廢水並循環再利用。結果顯示，人工濕地有效地去除循環水中的 TP、TSS 及無機性懸浮固體物，去除效率分別為 31、65 及 76%，並可保持養殖池內低污染物濃度水質。

德國 Shulz et al. (2003)[23]利用小型 SSF 溼地(長 1.4 m×寬 1.0 m)處理彩虹鱒魚養殖池所產生的排廢水，在相當短的 HRT (1.5~7.5 hr)條件下操作，探討污染物的去除效率，結果顯示 TSS 及 COD 去除效率分別 95.8~97.3%及 64.1~73.8，不受 HRT 影響；TP 及 TN 去除效率分別介於 49~68.5%及 20.6~41.8%，受 HRT 顯著影響。

上述國外的研究報導已證實人工溼地可適合於水產養殖排廢水的處理，經有效處理後可讓排廢水符合放流水標準。但應用於循環水養殖系統作為一種水質控制單元的研究發展，則相當罕見。

四、研究方法

1、循環水養殖系統：

本研究循環水養殖系統（圖 1）以實際養殖池水為處理對象，系統場址設置在台南市安南區一處郭姓養殖業者的養殖場。本人工溼地系統（constructed wetland system）（$105m^2$）是利用既有的漁塭（圖 2）整地後改造完成，由一個表面流動式（FWS，free water surface flow，約 30 m^2）溼地與另一個表面下流動（SSF，subsurface flow，約 $75m^2$）溼地所組成（圖 3），此人工溼地並與一個魚塭（$1125m^2$）以管線及幫浦建構成循環水養殖系統，循環池之養殖水以幫浦抽送至人工溼地淨化後再靠重力流回漁塭；另外，設置一個無循環水處理的魚塭（$1138m^2$）作為傳統魚塭養殖水質比較的控制組；兩處魚塭均飼養白蝦(*Litopenaeus vannamei*)。

人工溼地系統中的 FWS 溼地(30 m^2)，深約 1.8 公尺，並設置溢流管使水深保持約 1.5

公尺，FWS 溼地並種植浮水植物布袋蓮、水芙蓉，利用其豐富的根系來吸收養殖過程中白蝦的排泄物及分泌物，再加上飼料殘餘所產生的氮、磷，亦可吸附水中之懸浮固體物。由 FWS 溢流的循環水流到 SSF 濕地，SSF 溼地鋪設碎石及蚵殼，水深約控制在 1.2m，並種植挺水植物如蘆葦、香蒲、莎草、美人蕉，循環水經由碎石及蚵殼之孔隙而入滲至介質下層進行淨化，最後以重力流方式將處理過後之養殖水再排放至循環池中。

2、循環水養殖系統操作：

本研究進行了兩個試程的養殖及水質淨化試驗，第一試程自 93 年 7 中旬至 9 月中旬，第二試程自 93 年 12 月中旬至 94 年 5 月底，檢討人工溼地處理養殖池水之效能評估。養殖期間除了補充蒸散的水量外，均無換水。

循環水養殖池中設置一台抽水機，以時間控制器定時(每半小時進流 15 分鐘)將循環池養殖水抽送至 FWS 濕地，並於控制組養殖池及循環水養殖池各設置高效率曝氣機，以提供白蝦氧氣。養殖期間，第一試程及第二試程放養密度分別為每池 60,000 及 120,000 尾，約每平方有 5 及 10 隻。

3、水質分析：

本研究試養殖期間，每週一次採集循環水養殖池(簡稱為循環池)、人工濕地出流口、及控制組養殖池的水樣。並分析以下水質，包括：COD、SS、總氨氮、亞硝酸氮、硝酸氮、PO_4-P、大腸菌類、葉綠素 a、DO、pH、水溫等，依照 Standard Methods（APHA,1989）所列的方法進行。分析 COD、總氨氮(NH_4-N)、亞硝酸氮(NO_2-N)、硝酸氮(NO_3-N)、PO_4-P 及總磷(TP)之水樣，均預先以濾膜過濾，分析結果屬於溶解態。水中總大腸菌類數（total coliform）利用塗抹法以 Chromocult Coliform Agar（Merck, Germany）在 37℃下培養 24 小時，觀察鮭魚肉-紅色及深藍-紫色之獨立菌落，以 CFU/mL 表示。

4、統計分析

以 One-way ANOVA 評估循環水養殖池與對照池之間針對各項水質的顯著值(significance)。利用 Paired *t*-test 決定人工濕地進流水(亦即循環水養殖池池水)及出流水各項水質濃度的顯著值。

五、結果與討論

人工溼地處理養殖池水之試驗期間，操作下兩個試程的平均水質示於表 1，來探討溼地去除各污染物的成效。

1. 水力操作條件

第一試程循環水平均流量為 457 m3/d，相當於每日循環比約 0.21，循環水流經人工溼地的水力負荷平均為 4.35 m/d，水力停留時間平均為 4.96 h。第二試程操作時循環水平均流量為 414 m3/d，相當於每日循環比約 0.19，循環水流經人工溼地的水力負荷平均為 3.94 m/d，水力停留時間平均為 5.48 h。由於本研究使用較小的人工溼地面積：養殖池面積比(約 0.086)，因此與先前人工溼地應用於室內高密度循環水養蝦的的研究比較[16-17]，先前研究人工濕地所採用的水力負荷範圍 1.54~2.82 m/d 較本研究來的低，而水力停留時間介於 11.6~13.4 h 則較本研究來的較長。

2. SS 去除

由人工溼地進流—出流之水質分析結果顯示(圖 3)，人工濕地在第一及第二試程開始操作後 SS 去除即可達顯著(p<0.05)的去除效率，顯示相當短的啟動適應期。在第一試程及第二試程中 SS 的平均去除效率分別達 70.8 及 68.0%（表 2），兩個試程的 SS 去除效能相當一致。先前研究報導人工溼地處理室內高密度養蝦池的循環水[16-17]，對 SS 的去除效率介於

55~69%，與本研究相當接近。此結果顯示，本研究儘管提高水力負荷操作，但是不影響人工濕地對 SS 的去除效能，明顯看出人工溼地中 SSF 系統對 SS 之良好的處理能力（圖 3）。

由於溼地對 SS 的淨化，使得循環水養殖池的 SS 濃度經常低於沒有循環水處理的控制組養殖池。尤其在第二試程中，循環水養殖池 SS 濃度水質分析分別為 25±12 明顯低於控制組養殖池的 58±39（$p<0.05$）。顯示人工濕地有效地控制養殖池的 SS 水質。

3. 濁度去除

養殖水中濁度可能包含懸浮固體、浮游性藻類細胞或微細土質。人工濕地在第一及第二試程開始操作後濁度削減即可達顯著($p<0.05$)的去除效率(圖 4)，顯示相當短的啟動適應期。試驗期間，第一試程及第二試程中人工溼地對濁度的平均削減效率分別為 60.9 及 59.7％，兩試程之間無明顯差異（表 2）。先前研究中(16-17)，人工溼地對室內循環水養蝦系統的濁度消檢效率高達 91~99%，明顯高於本研究結果。可能的原因包括：(1)本研究為室外養殖，養殖水因浮游性藻類細胞生長而增加濁度(先前研究中循環水中濁度介於 1.1~3.8 NTU，而本研究循環水濁度為 7~25 NTU)，進而降低溼地對濁度的削減效率；(2)本研究水力負荷提高可能影響 SSF 溼地對戲小顆粒的攔截能力。儘管如此，本研究人工溼地仍顯示相當良好且一致的濁度消減能力（圖 4）。

表 1 顯示第一及第二試程中，循環水養殖池的水中濁度(16.5±5.2 及 16.5±6.1 NTU)均明顯低於控制組養殖池(23.0±9.8 及 29.8±10.2NTU)（$p<0.05$）。顯示人工濕地有效地控制養殖池的濁度水質。

4. 葉綠素 a 去除

葉綠素 a 可表示水中浮游性藻類細胞的指標。人工濕地在第一及第二試程開始操作後葉綠素 a 削減即可達顯著($p<0.05$)的去除效率(圖 5) ，顯示相當短的啟動適應期。試驗期間，第一試程及第二試程葉綠素 a 的平均去除效率分別為 50.9 及 51.9％（表 2）。另一項先前研究(15)中報導，人工溼地對室外循環水養蝦系統的葉綠素 a 去除效率高達 88%，明顯高於本研究結果。可能的原因為先前研究水力負荷較低僅 0.3 m/d。

由於人工濕地有效地去除葉綠素 a，導致第一試程中，循環水養殖池的水中葉綠素 a (30.8±29.1)僅略低於控制組養殖池(55.8±52.2 μg/l)（$p=0.12$）；但是到了第二試程中，循環水養殖池的水中葉綠素 a (16.9±11.4 μg/l)已明顯低於控制組養殖池(50.3±50.8 μg/l)（$p<0.05$）。顯示人工濕地有效地控制養殖池的葉綠素 a 水質。

5. BOD_5 去除

由圖 6 顯示，人工濕地在第一試程及第二試程開始啟動操作後 BOD 的去除即可達顯著($p<0.05$)的去除效率，顯示相當短的啟動適應期。整體而言，第一試程及第二試程的 BOD 平均去除效率分別達 47.3 及 58.2％（表 2），第二試程處理效率略高於第一試程。先前研究報導人工溼地處理室內高密度養蝦池的循環水(16-17)，對 BOD 的去除效率介於 37~54%，與本研究相當接近。此結果顯示，本研究儘管提高水力負荷操作，但是不影響人工濕地對 BOD 的去除效能，明顯看出人工溼地中 SSF 系統對 BOD 之良好的處理能力（圖 6）。

由於溼地對 BOD 的淨化，使得循環水養殖池的 BOD 濃度經常低於沒有循環水處理的控制組養殖池。表 1 顯示第一及第二試程中，循環水養殖池的水中 BOD(5.5±1.6 及 6.8±2.8 mg/l)均明顯低於控制組養殖池(7.4±3.2 及 10.5±2.6 mg/l)（$p<0.05$）。顯示人工濕地有效地控制養殖池的 BOD 水質。

由人工濕地可同時去除 SS、濁度、葉綠素 a 及 BOD 的結果顯示，有機性顆粒如：蝦體的排泄物、飼料殘餘及衍生的藻類細胞，在人工濕地中被截留或過濾後，進一步經由微生物的作用分解及礦化，因此不會造成有機物在水中累積。

6. 氮與磷的去除

由表 2 進出流的水質顯示，人工濕地對 NH_4-N、NO_2-N、NO_3-N 及 TP 並無顯著的去除效率。然而，循環水養殖池中的 NH_4-N 及 NO_3-N 還是有略低於控制組養殖池的趨勢。相對於先前的研究(16-17)，人工濕地可有效去除循環水中的含氮物質，NH_4-N、NO_2-N 及 NO_3-N 的淨化效果相當良好，平均去除效率分別可達到 58%、70%及 64%，本研究較低的氮化合物去除效能可能為水力負荷太高或水力停留時間太短，無法刺激生物轉換反應(如硝化作用及脫硝作用)的進行所致。未來將採較低的水力負荷操作，以評估本濕地場址對循環水氮化合物的去除效能。

六、結論與建議

本研究探討了人工溼地技術應用到魚塭循環水養殖中，利用溼地的自然淨水能力作為養殖廢水的淨化及管理單元，以維護魚塭養殖池水水質及降低養殖場排廢水的污染。獲得以下結論：

1. 人工濕地可有效的去除養殖循環水中的主要污染物包括：BOD_5 (47.3~58.2%)、SS(68~70.8%)、濁度(59.7~60.9)及葉綠素 a(50.9~51.9%)。
2. 由於人工濕地對污染物的處理效能使得循環水養殖池中 BOD_5、SS、濁度及葉綠素 a 濃度均較無循環的控制組養殖池顯著的低($p<0.05$)。
3. 本研究人工濕地對循環水中 NH_4-N、NO_2-N、NO_3-N 及 TP 並無顯著的去除效率。但是循環水養殖池中的 NH_4-N 及 NO_3-N 還是有略低於控制組養殖池的趨勢。
4. 人工濕地可提供一種節省能源、低設置成本之天然淨水技術應用於水產養殖產業之水質管理及排廢水改善污染排放上。本研究示範了將既有的魚溫改良成人工濕地—漁塭的室外循環水養殖系統，無須尋找可利用的土地，為一項工程容易進行、設置成本低廉，可提供魚民採用的生態工法。未來將持續證實人工濕地的水質控制對於增進魚蝦產量的效益影響。

七、計畫成果自評

本研究承國科會計畫編號：NSC－93－2211－E－041－002 贊助資金使計畫順利完成，除了獲得上述研究結果外，並可獲得以下論文發表：

1. 本研究提供嘉南藥理科技大學環境工程與科學系蘇瓊煜完成碩士論文。
2. 已投稿「第 30 屆廢水處理技術研討會」一篇論文。
3. 2004 年 11 月出席 the 2nd IWA Leading-Edge Conference on Sustainability 國際會議發表下列論文：Lin, Y. F., Jing, S.R., Lee, D.Y., Chang, Y.F., Chen, W.C. (2005b) Use of constructed wetlands in treating recirculating aquaculture water for in-door intensive shrimp production. *Water and Environmental Management Series*, in press.

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表 1 人工溼地操作結果與養殖池水質

採樣點	BOD_5（mg/l）	SS（mg/l）	濁度（NTU）	葉綠素 a（μg/l）
第一試程（*n*=16）				
控制組養殖池	7.4±3.2	28±12	23.0±9.8	55.8±52.2
循環水養殖池	5.5±1.6	24±16	16.5±5.2	30.8±29.1
人工濕地出流水	2.9±0.8	7±4	6.5±2.5	15.1±11.9
人工濕地處理效率(%)	47.3	70.8	60.9	50.9
第二試程（*n*=18）				
控制組養殖池	10.5±2.6	58±39	29.8±10.2	50.3±50.8
循環水養殖池	6.8±2.8	25±12	16.5±6.1	16.9±11.4
人工濕地出流水	2.8±1.3	8±4	6.6±3.2	8.1±5.2
人工濕地處理效率(%)	58.2	68.0	59.7	51.9

表 2 人工溼地操作結果與養殖池水質

採樣點	NH_4-N（mg/l）	NO_2-N（mg/l）	NO_3-N（NTU）	TP（μg/l）
第一試程（*n*=16）				
控制組養殖池	0.49±0.73	0.15±0.24	0.49±0.65	0.58±0.57
循環水養殖池	0.26±0.39	0.51±1.26	0.16±0.29	0.86±0.23
人工濕地出流水	0.50±0.56	0.32±0.33	0.19±0.37	0.80±0.26
第二試程（*n*=18）				
控制組養殖池	0.41±0.74	0.01±0.03	0.05±0.07	1.73±0.52
循環水養殖池	0.26±0.25	0.01±0.04	0.07±0.17	1.23±0.68
人工濕地出流水	0.42±0.42	0.01±0.02	0.89±3.46	1.05±0.60

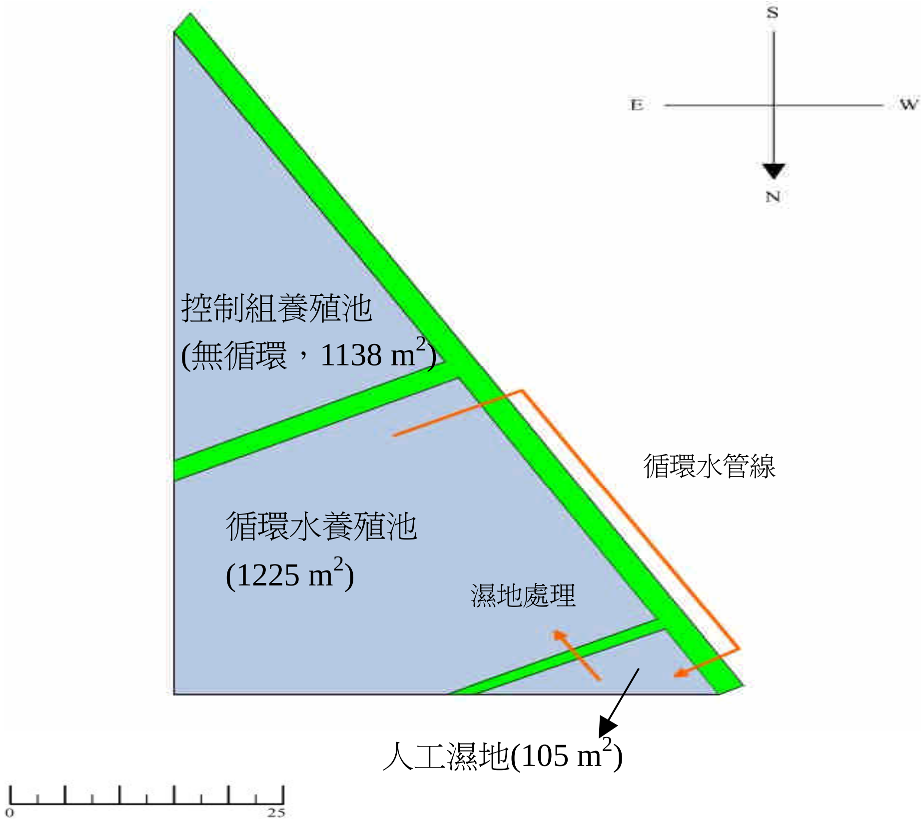

圖 1　「漁塭—人工溼地循環水示範系統」的配置圖

圖 2 魚塭整地前(照片左)及魚塭整地後結合人工溼地之循環水養殖系統

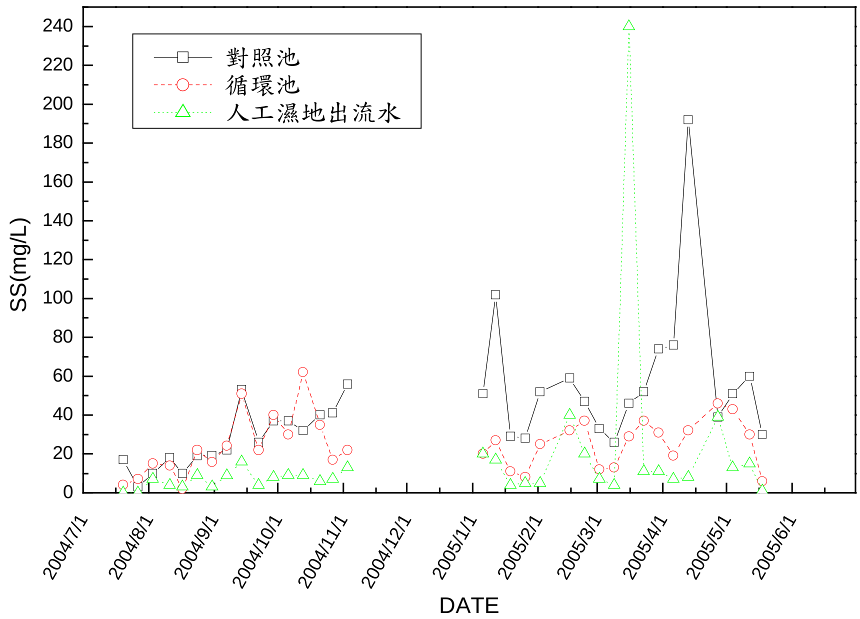

圖 3 兩試程操作期間 SS 之水質變化

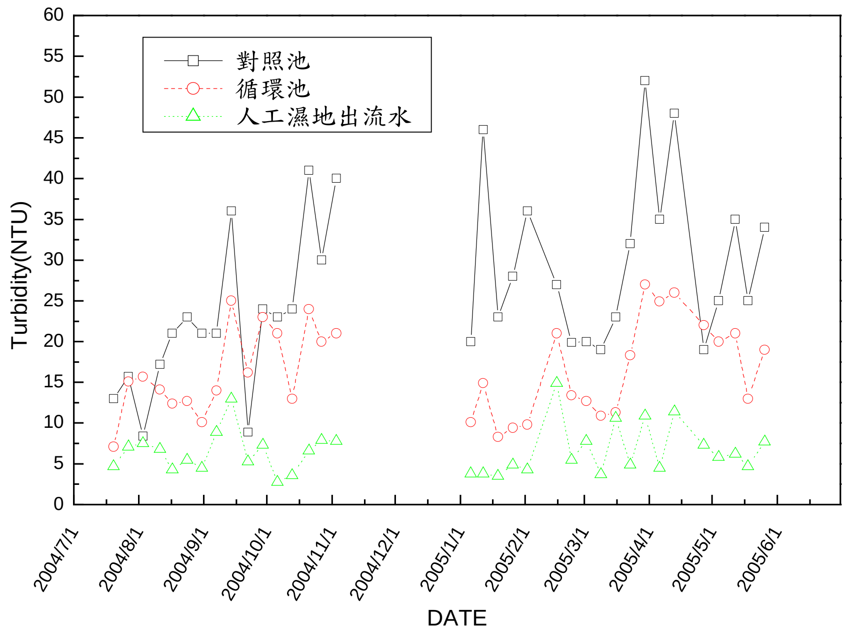

圖 4 兩試程操作期間濁度之水質變化

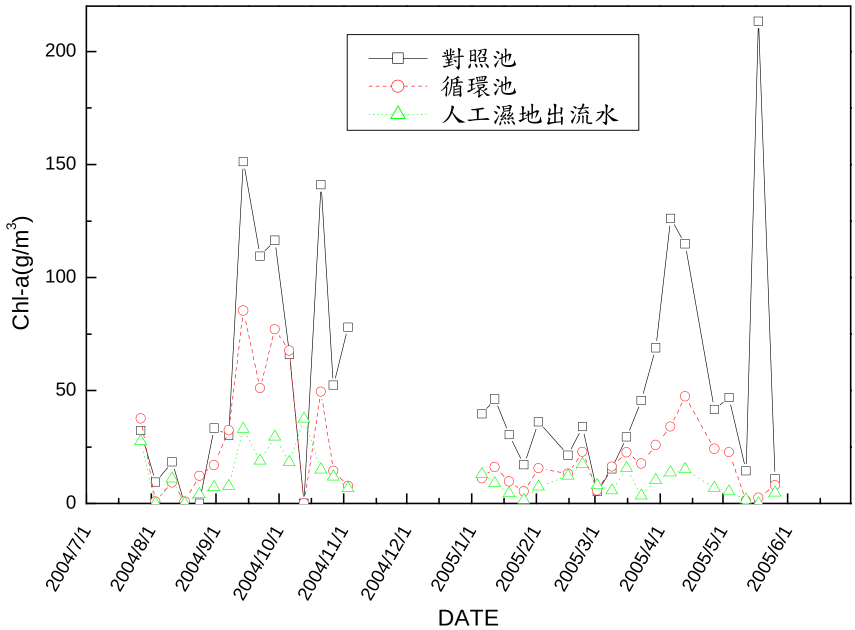

圖 5 兩試程操作期間葉綠素 a 之水質變化

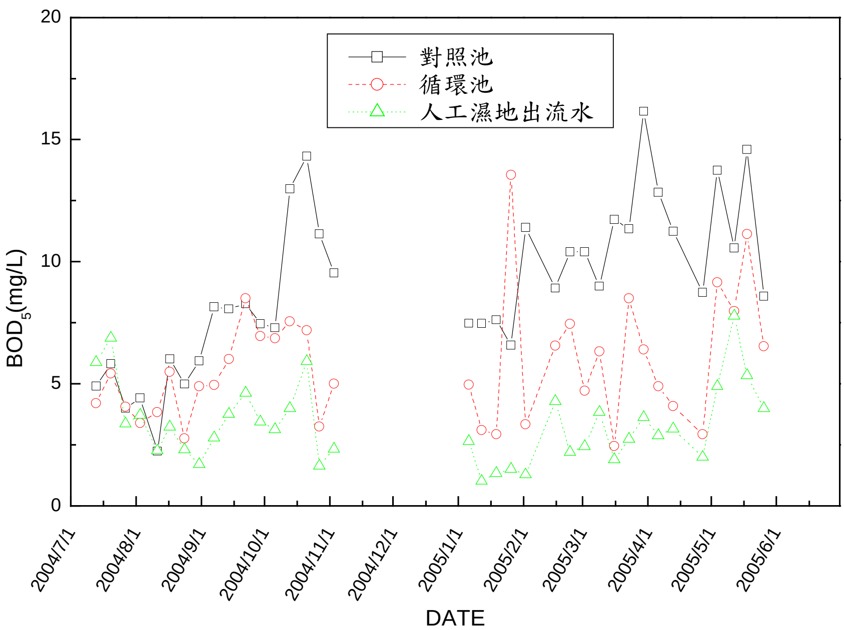

圖 6 兩試程操作期間 BOD_5 之水質變化

可供推廣之研發成果資料表

□ 可申請專利　☑ 可技術移轉　日期：94 年 9 月 30 日

國科會補助計畫	計畫名稱：**利用人工溼地管理水產養殖場水及廢水之研究** 計畫主持人：林瑩峰 計畫編號：NSC－93－2211－E－041－002　學門領域：環境工程
技術/創作名稱	循環水養殖之淨水設備與系統
發明人/創作人	林瑩峰
技術說明	中文：本技術係有關於一種循環水養殖之淨水設備，可包括有固體沉降收集之沉降池，將固體沉降後的循環水之溶解性有機物、氨氮、亞硝酸氮、硝酸氮等物質再進一步去除的表面流動式及表面下流動式之生態反應池，配合池中栽植的水生植物及土壤層與礫石層中的微生物，可使來自養殖池的循環水中之有害物質有效降低。經由上述方法淨化之處理水，則排入集水井中作由泵浦送回養殖池，形成一種利用自然生態機制作淨水循環的淨水設備。
	英文：This invention relates to an equipment of water purification used in the recirculating aquaculture, including a sedimentation pond that can collect solids, a surface flow ecological reaction pond and a subsurface flow ecological reaction pond a surface flow ecological reaction pond and a subsurface flow ecological reaction pond that can further remove organic matters, ammonia, nitrite and nitrate in the recirculating water from a culture pond. The two ecological reaction ponds, cooperating with plants in water and microorganisms on soil-rock media, can reduce the harmful matters. After the methods above, the recirculating water is drained into a well and then flows into the culture pond. The water purification equipment applying in the recirculating aquaculture uses the natural and ecological treatment mechanisms.
可利用之產業及可開發之產品	水產養殖業、水處理產業、生態工程產業
技術特點	本專利以自然生態淨水技術取代傳統習用的機械式淨水方法，淨化水產養殖過程所產生的污染物，以維護良好的養殖水質條件，並循環及回收再利用養殖廢水，使得在最節省初設成本及操作成本、節省養殖用水量的特性下，提高養殖產量並降低對環境的衝擊，達到養殖產業永續發展的目標。可應用於(1)室內淡水、鹹水、半鹹水循環水養殖；(2)室外淡水、鹹水、半鹹水循環水養殖；(3)景觀水池及生態水池的水質維護。

推廣及運用的價值	台灣養殖業盛行，唯大多屬於傳統魚塭養殖，此種養殖方式耗用龐大水資源、易造成地下水超抽及地層下陷等環境衝擊。循環水養殖為減輕環境衝擊的重要途徑，本技術可提供低成本、有效率、容易操作的循環水淨水方法，並提高養殖產量，對台灣或大陸養殖產業市場具有需求性。

※ 1.每項研發成果請填寫一式二份，一份隨成果報告送繳本會，一份送　貴單位研發成果推廣單位（如技術移轉中心）。

※ **2.本項研發成果若尚未申請專利，請勿揭露可申請專利之主要內容。**

※ 3.本表若不敷使用，請自行影印使用。

行政院國家科學委員會補助國內專家學者出席國際學術會議報告

民國93年11月30日

報告人姓名	林瑩峰	服務機構及職稱	嘉南藥裡科技大學環境工程與科學系 教授
時間 會議地點	2004年11月8~10日 澳大利亞,雪梨(Sydney, Australia)	本會核定補助文號	93-2211-E-041-002-
會議名稱	(中文) 第二屆IWA永續前瞻國際研討會 (英文) the 2nd IWA Leading-Edge Conference on Sustainability		
發表論文題目	(中文) Use of constructed wetlands in treating recirculating aquaculture water for in-door intensive shrimp production (英文)利用人工濕地於室內高密度循環水養蝦之水質處理		

一、 參加會議經過

永續前瞻國際會議(Leading-Edge Sustainability Conference, LES)是國際水協會(International Water Association, IWA)所發起，每兩年舉辦一次有關水資源永續利用的前瞻性管理策略及實用技術的國際會議，今年在澳大利亞雪梨市的InterContinental Hotel舉辦，迄今已成功舉辦了兩屆。

水資源永續利用乃是一項結合不同專業訓練與方法的新興領域，達到保護及強化生態系統的功能，因而獲得利益的回報。今年的 LES 會議，乃以水匱乏環境的永續性(Sustainability in Water Limited Environments)做為研討主題。由於水匱乏的生活社區環境特別需要提升水的供給效率，因此如何透過回收再利用、經濟效益的動機或雨水再利用等策略，並且在考慮某些危害因子(如衛生)的情況下，達到提升水供給效率的需求，為本次研討會關注的課題。

LES為一個規模不大的研討會，與會者約有來自世界約20個國家的100位代表與會，這些與會者均屬於大學、研究機構或政府單位具有各個領域，如環境工程與科學、衛生工程、自然資源管理極保育、水管理政策等領域的專家。研討方式分為：口頭論文發表(oral session)及壁報發表(poster session)。分三天七個議題進行研討，議題分別為：I、缺水環境的挑戰；II、決策的新方法；III、健康、衛生與風險；IV、針對永續的系統規劃；V、針對永續的管理決策；VI、生態系統功能；VII、永續性的前瞻技術。總計約60篇論文的發表。

這些論文涉及題材廣泛，研究內容深入，不少論文具有很高的學術水準。國內前往與會的專家學者僅有本校李得元副教授及本人。

二、 論文發表

此次筆者有兩篇論文的發表。均為筆者與本校荊樹人教授、李得元副教授所合著的論文：「Use of constructed wetland in treating recircilating aquaculture water for in-door intensive shrimp production」及「Constructed wetlands in campuses for wastewater treatment, water reuse and landscape enhancement」，前一篇被安排口頭論文發表再11月10日上午，後一篇為壁報發表。口頭發表的論文已通過審查，全文將收錄在IWA所發行的Water and Environmental Management Series (WEMS)專書中，預計於2005年12月出版。

三、 與會心得

會中較引起本人興趣的研究為有關Ecological Sanitation(生態衛生技術)的發展觀念及趨勢。目前在多數已開發國家及開發中國家中，針對人類生活所產生的排泄物及廢水的管理策略多採用”flush and discharge”的思維，將人類產出物視為廢棄物及廢水，靠工程技術(亦即下水道管線及污水處理廠)將廢水及排泄物妥善處理達到符合衛生的要求，但是所需建設及營運費用龐大，許多開發中國家及未開發國家均無法負擔，在無污水工程的配合下”flush and discharge”反造成環境的污染。況且，排泄物及廢水實際蘊藏人類作物所需的營養物(nutrient，如氮、磷、鉀)及可利用得水資源，若以”flush and discharge”方式管理則無法有效利用這些資源。Ecological Sanitation則是推翻了”flush and discharge”的思維，而是將排泄物及廢水視為資源而加以回收及在利用，在此分類收集及處理相當重要，其作法如下：

1. 來自住家屋頂、陽台的雨水，污染性相當低，可經由簡單的篩濾去除顆粒雜質將雨水儲存後再利用。然而，有些學者關心雨水逕流可能夾帶鳥類糞便，其對雨水衛生性質造成影響。此部份雨水適合回收於馬桶及地面沖洗、洗車等。
2. 來自洗手、洗澡、廚房清洗的水稱為灰水(gray water)，理論上含有有機物、氮、磷等污染物，但是病源菌的污染較輕微，可分開管線收集，再利用較低成本的生態工法(如人工濕地)可妥善處理，處理水可回收於園藝及農作澆灌、或馬桶及地面沖洗等。
3. 尿液(urine)及其沖水稱為黃水(yellow water)，而糞便(feces)及其沖水稱為黑水(black water)。由於尿液所含的氮、磷、鉀營養物含量遠高於糞便，且病源菌含量相當低，因此Ecological Sanitation主張經由廁所(馬桶及管線)的改良將尿液及糞便分開收集，黃水的部分可經由簡易的消毒(如加熱)後，即可回收可觀的營養物資源，使用於作物施肥上；而黑水的部分，污染性及病源性最高，則須以傳統的工程技術(如厭氧消化、堆肥等方法) 將它穩定化，在回收於有機肥料的使用上，不過經由分類收集後，所需處理的黑水體積已大大減少。
4. Ecological Sanitation須結合建築結構的改良及居民生活習慣的改變方可達成。

台灣年降雨量雖然豐富，但是因降雨期過度集中、地形陡峭及水體環境普遍污染，常使台灣名於缺水國行列，如何在缺水條件中永續的利用水資源為國家發展上重要的課題。上述Ecological Sanitation的做法不僅可有效收集利用雨水，亦可妥善處理廢污水達成公共衛生的要求，並可回收作物需求的營養物，實可提供國內在污水工程及水資源管理上的參考。

三、攜回資料名稱及內容

「Conference Proceeding in CD for the 2nd Leading-Edge Conference on Sustainability」。

Use of constructed wetlands in treating recirculating aquaculture water for in-door intensive shrimp production

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Abstract A commercial-scale recirculating aquaculture system was installed to demonstrate the effectiveness of constructed wetlands in treating the recirculating aquaculture water and the success in production of Pacific white shrimp (*Litopenaeus vannamei*). The system consisted of an indoor culture tank (64 m^2) and an outdoor wetland based water treatment unit that included a settling cell (1.5 m^2), a free water surface (FWS) wetland (12 m^2), a subsurface flow (SF) wetland (15.7 m^2), and a sump (1 m^2). Throughout the whole study of 126 days, the shrimp feed totalled to 328 kg and final shrimp body weight reached a food size of 12.3 g in average. Hydraulic loading rate of the FWS-SF wetlands was initially controlled at about 0.62 m/day, and gradually increased to 2.82 m/day in the final culture phase. Solids in the recirculating water were efficiently removed through the FWS-SF wetlands by 69% (measured as total suspended solids) and 98% (measured as turbidity). Microbial mineralization and nitrification of the wetlands significantly reduced 5-day biochemical oxygen demand, total ammonia nitrogen and nitrite levels from the recirculating water by 53, 58, and 70 %, respectively. Nitrate was not prominently accumulated in the culture tank water during this study because denitrification occurred in the wetlands and exhibited an effective nitrate reduction (64%). At the end of the study, total weight of the harvested shrimp was 354 kg, and shrimp survival rate was estimated to be 72%. Accordingly, shrimp production per unit culture area was 5.5 kg/m^2, which is around 8 times higher than the production of conventional pond aquaculture. Constructed wetland was demonstrated to be a sustainable technology for regulating water qualities and saving water usage in a recirculating system for in-door intensive shrimp production.

Keywords Constructed wetland, recirculating aquaculture system, Pacific white shrimp, aquaculture wastewater.

Introduction

Aquaculture is an important industry in Taiwan to supply seafood both for domestic demand and exporting trade. However, pond aquaculture requires a large amount of water resource and land area, and produces a polluted discharge, thereby creating various environmental impacts. Since most surface water bodies had been widely polluted, groundwater became the major water resource for aquaculture industry. Over withdrawal of groundwater has led to a considerable ground subsidence and seawater intrusion in several coastal areas of western Taiwan, where aquaculture intensively prevails. To reduce the impacts of aquaculture on environment, government promoted a Guiding Program for Aquaculture Industry in 1991 and a Ground Subsidence Control Program in 1995 (Hu, 1999). In these programs, development of recirculating aquaculture systems in fish and shrimp farms is one major and important approach to achieve sustainability in water usage for aquaculture.

A recirculating aquaculture system, integrating wastewater treatment process into aquaculture production to manage water quality, allows for intensive culture with limited pollutant discharge, thus reducing water and land usage, and minimizing adverse environmental impacts. Treatment units, such as sand filter, mechanical screen, submerged biofilters, rotating biological contactors, and/or fluidized bed reactors etc., are typically used in a recirculating aquaculture system (Tseng et al., 1998; Yang et al., 2001). These conventional methods can efficiently remove the pollutants and toxic materials from aquaculture wastewater. However, they require much higher capital cost and energy, depend on frequent maintenance, and produce sludge. These disadvantages have limited the will of farmers to use the recirculating aquaculture system instead of pond aquaculture. Accordingly, an effective and low-cost wastewater treatment process is imperative for sustainable development of aquaculture in Taiwan.

Previous studies have demonstrated that constructed wetlands are technically and economically feasible to remove the major pollutants from catfish, shrimp, milkfish, and rainbow trout pond effluents (Schwartz and Boyd, 1995; Sansanayuth et al., 1996; Lin et al., 2002a, 2002b; Schulz et al., 2003), and can act as a cost effective filter using in a recirculating aquaculture system (Zachritz and Jacquez, 1993; Tilley et al., 2002; Lin et al., 2003). However, the success of this approach in aquaculture production for field application is still seldom reported.

In this study, a commercial-scale recirculating aquaculture system was installed to demonstrate the effectiveness of constructed wetlands for managing water quality and controlling water usage, and the success in intensive shrimp production. The cost of the wetland based treatment process was also analysed to compare with a conventional treatment process.

Materials and methods

Recirculating aquaculture system

The recirculating aquaculture system was built in a fish farm at Tainan County, Taiwan during March 2001. This system mainly consisted of an indoor culture tank and an outdoor wetland based water treatment unit (Fig. 1), which was made of brick and concrete in main body. Pipelines made of polyvinyl chloride were installed to connect the culture tank and treatment unit for conveying the recirculating water.

The culture tank was 8 m × 8 m × 1.5 m (inner length, width and height) in size, maintaining a water depth of around 1.2 m. Tube diffusers, connected to an air compressor, were installed in the culture tank to supply oxygen for shrimp culture. Tank water flowed continuously to the water treatment unit by gravity, and the flow rate was controlled by a

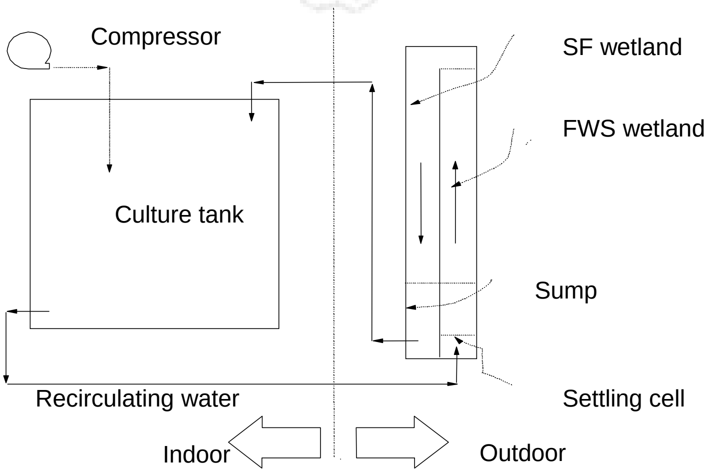

Figure. 1 Schematic diagram of a recirculating aquaculture system integrating constructed wetlands.

gate valve.

The water treatment unit was measured by 2.1 m × 15.2 m (inner width and length), and was divided longitudinally by a brick-concrete wall (10 cm thick) to form a U shape ditch with an equal inner width of 1 m. This ditch was separated into four cells: a settling cell, a free water surface wetland (FWS cell), a subsurface flow wetland (SF cell), and a sump.

The settling cell (inner length of 1.5 m) received the recirculating water from the culture tank. A perforated acrylic baffle was installed across the wide direction of the cell at 25 cm from the inlet end for flow distribution. The bottom of the cell sloped at about 14% towards the inlet end, with a sludge hopper located at the bottom of the inlet end. Sludge was occasionally siphoned out from the hopper. The deepest water depth was around 1.2 m.

The effluent from settling cell flowed through a perforated full-width brick-concrete wall into the FWS cell. The FWS cell (inner length of 12 m) contained a 30 cm layer of local soil (Jender silt loam, 25°37’N, 166°55’E) at the bottom and 40 cm of averaged water depth above the soil layer.

The effluent of the FWS cell entered the SF cell through a perforated full-width brick-concrete wall. The SF cell (inner length of 15.7 m) included 80 cm of river gravel (nominal diameter 10 to 20 mm), providing a porosity of 45%, and 65 cm of averaged subsurface water flow within the gravel layer. A lateral perforated manifold, as a collection drain, was installed at the bottom of outlet end of the SF cell. The manifold was extended to the sump (inner length of 1 m) and connected with a 90^0 elbow to control the water depth of wetland cells. After re-aeration in the sump, the wetland treated effluent was recycled to the culture tank by a submerged pump.

Cattail (*Typha angustifolia L.*) and common reed (*Phragmites australis*) were planted in the FWS and SF cell, respectively, both with initial density of around 6 plants/m^2 in the late March 2001.

Shrimp culture conditions

Shrimp culture was conducted during a warm season from 13 June to 17 October 2002. Postlarvae (PL) of Pacific white shrimp (*Litopenaeus vannamei*) with initial body weights of 5 to 6 mg/PL were introduced into the culture tank with stocking densities of around 625 PL/m^2. A brackish groundwater containing approximately 0.3% salinity was used for shrimp culture in this study. The shrimp were fed with a powder diet during the initial four weeks of culture and a pellet diet after the four weeks of culture. These commercial diets contained around 45% protein, 2 % fat, 3% cellulose, 17% ash, and 11% water. The feeding rate was adjusted according to the intake rate of the shrimp. The shrimp were fed manually at around 8 A.M. and 4 P.M. each day. After four weeks of culture, 30 shrimps were taken from the culture tank every two weeks, and their body weight and length were measured to estimate the shrimp growth.

Water sampling and analysis

Water samples were taken twice a week from outflow end of the culture tank, influent of the FWS cell, effluent of the FWS cell, and effluent of the SF cell. Such sampling was usually performed at around 10 A.M. on each sampling date. The samples were analyzed for total suspended solids (TSS) and turbidity. The filtrates left by filtering water samples through glass-fiber filters were measured for 5-day biochemical oxygen demand (BOD_5), total ammonium nitrogen (TAN), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), and orthophosphate (PO_4-P). Temperature, pH and dissolved oxygen (DO) of water in the sampling locations were also monitored. All the analytical measurements were carried out according to Standard Methods (American Public Health Association, 1995).

Tests for significant difference in water quality between influent and effluent of the treatment cells were determined by paired *t*-tests at a significance level of 0.05 (OriginLab, 1996) for each set of data.

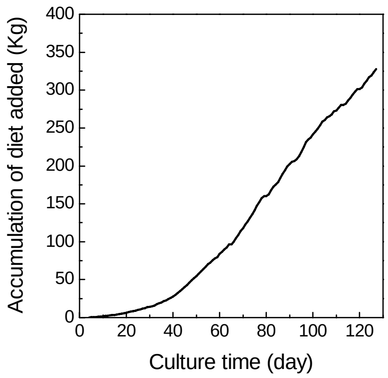

Figure 2 The increasing curve of shrimp diet added in culture tank of the recirculating aquaculture system.

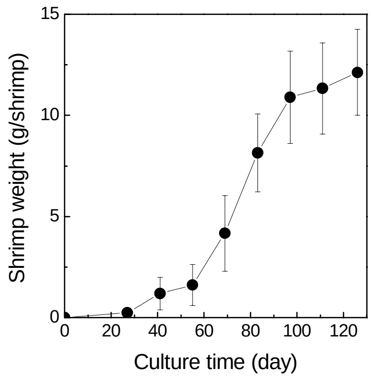

Figure 3 Growth curve in term of weight of shrimp in the recirculating aquaculture system.

Results and discussion

Shrimp culture and growth

The increasing curve of shrimp diet added was found corresponding with shrimp growth curve (Figures 2 and 3). Shrimp grew slowly in the first 30 days, exhibiting an initial growth phase. Shrimp growth rate gradually increased and reached a rapid growth phase during days 55 to 95 (Figure 3). A declining growth phase was observed afterward because crowding effect due to intensive culture. Throughout the whole study of 126 days culture, the shrimp diet totaled to 328 kg and final shrimp body weight reached to a food size of 12.3 g in average. Maximum growth rate of shrimp was recorded to be 2 g/shrimp/week, with an average growth rate of 0.1 g/shrimp/day.

Recirculating water control

Flow rate of recirculating water into the treatment unit was initially controlled at about 17.3 m^3/day (equivalent to a hydraulic loading rate of 0.62 m/d for the FWS-SF wetlands), and gradually increased to 78 m^3/day (hydraulic loading rate of 2.82 m/d) in the final culture stage (Figure 4). This flow control strategy was made to correspond with the tendencies of diet added (i.e., pollutant loaded) and shrimp growth with culture time. Small flow rate would be sufficient to handle the pollutants generated in the initial culture phase, with also saving the pumping cost for recirculating water.

Performance of constructed wetlands and water quality

Prior to this study, two phases of culture using this same recirculating system had been carried out to collect data for determining the wetland area required for management of water quality in the intensive shrimp aquaculture from April to June 2001 and from August 2001 to January 2002, respectively (Lin et al., 2005). This study is indeed the third phase of culture. Macrophytes in constructed wetlands had reached a stable density more than 90 plants/m^2 since the end of the second phase. Macrophytes were not purposely harvested except dead plant detritus were occasionally removed to avoid a blockage problem of water flow. Continuous-flow operation of the constructed wetlands was ceased during the period between two phases, but still maintaining the water depth to sustain the growth and survival of both macrophytes and microorganisms in wetland cells.

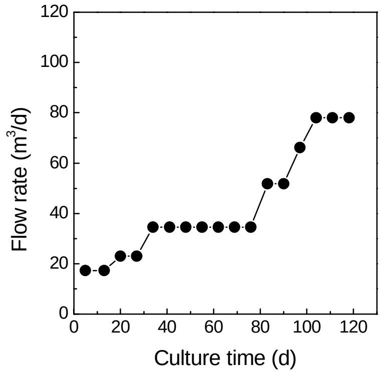

Figure 4 Flow rate of recirculating aquaculture water through constructed wetland system during shrimp culture.

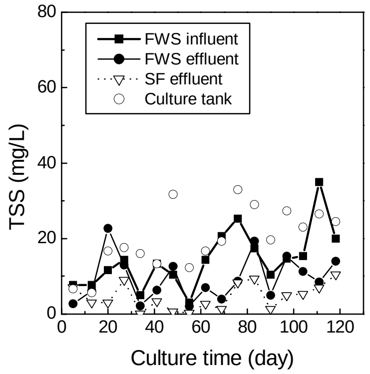

Figure 5 Time course of TSS at various sampling positions in the recirculating aquaculture system.

Table 1 Treatment results (mean ± standard deviation) for various parameters of water quality by the FWS-SF wetlands (n = 18).

Parameter	FWS influent	FWS effluent	SF effluent	Average removal efficiency (%)	Culture tank
pH	8.2±0.6	8.1±0.5	7.8±0.5	-	8.1±0.2
Alkalinity (as $CaCO_3$ mg /L)	347±23	342±18	334±16	-	345±22
DO (mg/L)	4.7±2.4	2.4±2.7	0.56±0.65	-	6.6±0.4
TSS (mg/L)	14.5±7.8	9.5±6.1	4.6±3.4	69±23	20±8
Turbidity (NTU)	1.1±0.9	0.35±0.71	0.01±0.02	98±2	1.9±1.2
BOD_5 (mg/L)	6.6±4.9	5.3±4.1	2.7±1.9	53±25	7.3±5.9
TAN (mg/L)	0.58±0.65	0.64±0.62	0.20±0.25	58±25	0.37±0.24
NO_2-N (mg/L)	0.48±0.47	0.37±0.37	0.08±0.09	70±32	0.43±0.44
NO_3-N (mg/L)	2.79±2.9	2.92±2.95	1.98±2.73	64±35	3.13±3.14

There was a slight decrease of pH and alkalinity in recirculating water flowing through the FWS-SF wetlands (Table 1). This decrease might be due to nitrification occurring in the treatment wetlands. However, pH of water in the culture tank was stably maintained at a suitable range of 7.7~8.5 without any pH adjustment. Solids in the recirculating water were efficiently removed through the FWS-SF wetlands by 69% (measured as TSS reduction) and 99% (measured as turbidity reduction), leading to a tank water of 20±8 mg/L for SS and 1.9±1.2 for NTU (Figure 5 and Table 1). Solids in the recirculating aquaculture water are mostly generated from feed residue and shrimp excreta. They can be removed by constructed wetlands via sedimentation and filtration that occur within plant stems and roots and within the gravel that forms the substratum. Organic solids can be further stabilized in wetlands through biological processes such as microbial degradation (Lin et al., 2002b). Thus, solids accumulation in wetland cells was ignored during this study, and processing of sludge produced from wetlands was not required.

Microbial mineralization and nitrification occurring in the treatment wetlands significantly ($p < 0.05$) reduced BOD_5, NH_4-N and NO_2-N levels in the influent water by 53, 58, and 70 %, respectively, and resulted in consistently low levels of BOD_5 (7±6 mg/L), TAN (0.37±0.24 mg/L), and NO_2-N (0.43±0.44 mg/L) in culture tank water (Table 1, Figures 6~8). These levels were well below the safe levels for rearing *L. vannemei* juveniles (2.44~3.95 mg/L for TAN and 6.1~25.7 mg/L for NO_2-N) reported by Lin and Chen (2001, 2003). Moreover, the simultaneous reduction of TSS and BOD_5 from the influent to effluent indicates that degradation and stabilization of solids actually occurred in the constructed wetlands. The results of transitions of influent-effluent water quality (Figures 5~9) suggests that the constructed wetlands required a brief start-up period, less than 10 days, to achieve a stable and consistent removal of major pollutants when initiating a new culture phase.

Although nitrification efficiently occurred in wetlands, NO_3-N was not accumulated in the SF effluent. On the contrary, NO_3-N concentrations of the SF effluent were always lower than those of the FWS influent in 83% of samples (13 of 16) (Figure 9). This result led to 64% of mean nitrate reduction from FWS influent to SF effluent (Table 1). These observations might be caused by the denitrification performance of the constructed wetlands. Consequently, NO_3-N in culture tank water exhibited a low level of 3.13±3.14 mg /L during

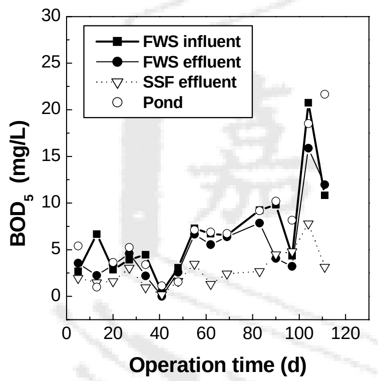

Figure 6 Time course of BOD_5 at various sampling positions in the recirculating aquaculture system.

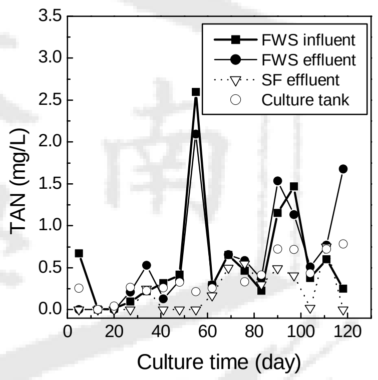

Figure 7 Time course of TAN at various sampling positions in the recirculating aquaculture system.

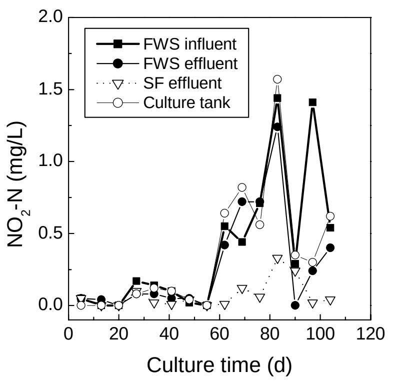

Figure 8 Time course of NO_2-N at various sampling positions in the recirculating aquaculture system.

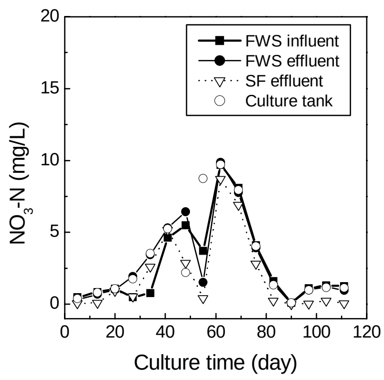

Figure 9 Time course of NO_3-N at various sampling positions in the recirculating aquaculture system.

Table 2 Capital cost analyses of the wetland based treatment unit for an indoor recirculating aquaculture system.

Description	Cost (US$)	Unit Cost (US$/m^2)	Cost (%)
Basins construction	7,900	39.5	65.6
Gravels and soil	2,670	13.35	22.1
Planting	270	1.35	2.2
Electric, pumping and pipe systems	1,200	6	10.1
Total	12,040	60.2	100

Basis: 200-m^2 scale concrete made basin.

this study (Table 1). The ability of wetland denitrification here is shown more effective than that in the previous two phases of culture (Lin et al., 2005), probably due to a denser macrophyte achieved in this study providing more available organic carbon to boost denitrification.

The performance of treatment wetlands in this study is easily comparable to that of the conventional treatment process (including micro-screen, foam fractionator, and biological filter) employed in a recirculating shrimp production system reported by Davis and Arnold (1998), in which TAN and NO_2-N were maintained at the range of 0.36~1.16 and 0.30~1.48 mg/L, respectively, in culture chamber.

Shrimp production and water usage

At the end of the study, total weight of the harvested shrimps was 354 kg, and shrimp survival rate was estimated to be 72%. Overall food conversion ratio, defined as the ration of the total amount of diet added to the increment of total weight of shrimps harvested, was estimated to be 0.92. This efficient conversion of food to shrimp growth might be resulted from a suitable water quality and health environment managed by constructed wetlands. Accordingly, shrimp production per unit culture area was 5.5 kg/m^2, which is around 8 times higher than shrimp production in conventional earthen pond aquaculture. This shrimp production is rather successful in comparison with an indoor recirculating white shrimp culture system employing conventional treatment processes (Lin et al., 2000), in which a higher stock density (1300 PL/m^2) with a higher initial weight (66 mg/PL) was used, and achieving a food size of 10~11 g/shrimp and a production of 6.7 kg/m^2 after 105 days culture.

No water discharge or displacement occurred during this study, except for replacing water lost through evaporation.

Cost analysis for a wetland based treatment unit

Capital cost analyses of the wetland based treatment unit for an indoor recirculating aquaculture system is provided in Table 2. These costs were estimated base on a 200-m^2-scale concrete made treatment unit scaling up from the results of this study. Basin construction and gravel are the two major cost items, accounting for 65.6 and 22.1 % of the total capital cost, respectively. The capital cost will be further reduced if treatment wetlands are built of earthen basin and gravel is substituted by recycling substrates.

Chen et al. (2002) analysed cost and benefit of a 0.1 ha automatic indoor recirculating shrimp culture system with 420 m^2 required for culture tank. In that system, capital cost of the conventional wastewater treatment process used (including micro-screen, biological filter, electrical disinfection device) was approximately US$71,700 and contributed to the most significant part (34%) of the total capital cost. If constructed wetland technology is applied to such scale of shrimp culture (*i.e.*, 420 m^2 for culture area), a land area of 200 m^2 will be required for construction of the wetland based treatment unit (treatment wetland plus a settling basin), according to an area ratio (0.47) of treatment unit to culture tank used in this study. As a consequence, the capital cost of the wetland based treatment unit for an indoor recirculating shrimp culture system will be US$12,040 that is less than 20% of the conventional wastewater treatment process. Operation and maintenance costs of the wetland based treatment unit will mainly include electricity demand for pumping the recirculating water.

Conclusions

Recirculating aquaculture systems incorporating conventional mechanical treatment processes have been development for decades for sustainability in aquaculture. However, the systems are not widely used probably because they have not been cost effective for large-volume culture systems. This study demonstrated that a wetland based treatment technology, mainly including two types (free water surface and subsurface flow) of constructed wetland, is an economic and efficient approach to manage the water usage and water quality for intensive aquaculture production. Wetland treatment efficiently and simultaneously removed TSS (69%), turbidity (98%), BOD_5 (53%), TAN (58%), NO_2-N (70%), and even NO_3-N (70%) from recirculating water, leading to an appropriate and non-harmful water quality to aquaculture. The culture system of this study gained a 5.5 kg/m^2 of shrimp production, which is comparable to the culture system using a conventional treatment process and is 8 times higher than the production of earthen pond aquaculture. On the basis of serving equal culture scale, the capital cost of a wetland based treatment unit is only about 20% of a conventional treatment process. Accordingly, incorporating constructed wetlands technology into a recirculating aquaculture system will significantly reduce the overall cost and enhance sustainability of the system.

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