行政院國家科學委員會專題研究計畫　成果報告

人工溼地技術永續管理水產養殖場水及廢水之研究(II)

計畫類別：個別型計畫
計畫編號：NSC94-2211-E-041-023-
執行期間：94 年 08 月 01 日至 95 年 07 月 31 日
執行單位：嘉南藥理科技大學環境工程與科學系(所)

計畫主持人：林瑩峰
共同主持人：張翊峰，余元傑
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報告類型：精簡報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫涉及專利或其他智慧財產權，2 年後可公開查詢

中　華　民　國 95 年 10 月 31 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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執行單位：嘉南藥理科技大學　環境工程與科學系

中　華　民　國　95　年　7　月　31　日

中文摘要

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。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）以管線及抽水機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*)。

實驗結果顯示，循環水養殖池與經由濕地處理後進出流水之SS平均水質濃度在第一試程中分別為 21±14 及 6±5mg/L；第二試程中為 23±12 及 8±5mg/L；第三試程中為 37±10 及 15±15mg/L，平均去除效率各試程分別為 78、54 及 59%，BOD_5平均水質濃度在第一試程中分別為 5.6±1.6 及 2.9±0.75 mg/L；第二試程中分別為 6.2±3.0 及 3.1±1.7 mg/L；第三試程中分別為 6.6±2.2 及 4.8±1.6 mg/L；平均去除效率各試程分別為 40、46 及 27%，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%。在有飼料的投入約 72 天後，循環水養殖池白蝦的生長已大於控制組養殖池，推估可能是因為控制組養殖池後期污染物濃度略高，因為本實驗控制組養殖池不像循環水養殖池之廢水有經過溼地處理過後循環再利用，所以可能導致池內污染越來越高，進而影響其生長速度。

關鍵詞：人工溼地、循環水養殖、白蝦

Abstracts

Aquaculture in earthen ponds has been conventionally and widely used. However, such culture process typically requires a large amount of water resource, land area and energy, and produces a polluted effluent, thereby resulting in a great impact on environment. Additionally, the accumulation of the feces from fish and the residues of food normally cause deterioration of the pond water and further reduce the production and quality of the aquaculture products.

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.

Results of water monitoring of influent-effluent showed that constructed wetland effectively reduced TSS from 21±14 to 6±5mg/L in trials 1, 23±12 to 8±5mg/L in trials 2, and 37±10 to 15±15mg/L in trials 3, (removal efficiencies ranging from 54 to 78%), reduced BOD from 5.6±1.6 to 2.9±0.8 mg/L in trials 1, 6.2±3.0 to 3.1±1.7 mg/L in trials 2, and 6.6±2.2 to 4.8±1.6mg/L in trials 3, (removal efficiencies ranging from 27 to 46 %). Besides, constructed wetland showed good removal efficiency in NH_4-N、NO_2-N and NO_3-N (58%、70% and 64%) from the recirculating aquaculture water. After 72 days of shrimp culture, the weight and length of shrimps in the recirculating aquaculture system exceeded that in the control fishpond, because the recirculating aquaculture system can control higher water quality, through the treatment wetlands, in fishpond and reduce pollutant level, thus increasing shrimp growth rate.

***Keywords*: c**onstructed wetlands; recirculating aquaculture; shrimp

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]。

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[2]。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。美國亦曾利用FWS型溼地處理鯰魚(catfish)漁塭之排廢水[3]，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%。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[4-9]。

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。建立控制組養殖池與循環水養殖池做對照，並對溼地的水質進行採樣及各項參數之分析，以探討溼地去除污染物的處理機制。

文獻探討

濕地雖然是自古即存在的自然淨化系統，但將其應用在水污染防治及水資源保育上，則是

近二、三十年才逐漸地發展並受到國際間的重視。這十幾年間，無論是已開發國家（如美國、英國、挪威、澳大利亞）或開發中國家（如南非、印度、中國、斯洛凡尼亞）均陸續有許多學者參與計畫研究，並有超過 1000 個濕地系統被實際應用。這些文獻報導又以人工濕地系統佔絕大多數，其研究與應用目的，大多是將人工濕地當作二級處理程序或高級處理程序，用以處理都市污水、工業廢水、畜牧業廢水、垃圾掩埋場(或礦場)滲出水、農地逕流水等。而從研究結果中可知，對於廢（污）水中的主要或微量污染物，例如懸浮固體、有機物質、氮磷營養物、重金屬及微生物，人工濕地均可提供良好的去除效能。

國外許多已開發國家(如美國、德國、新加坡)及水產養殖盛行的開發中國家(如泰國)都已關注並著手解決水產養殖業所造成的環境衝擊及生態破壞問題，而解決之道首重於水污染防治工作的進行。例如，泰國政府甚至訂出比我國更嚴格的漁場排廢水標準：BOD_5<10 mg/L、並禁止漁塭底泥排放至水體。美國環保署及各州針對水產養殖排水所訂出的標準亦相當嚴格：BOD_5<30 mg/L、SS<30 mg/L、TP 0.17 mg/L、總氨氮 1.77 mg/L、亞硝酸氮 0.83 mg/l，硝酸氮 16.9 mg/l，同時也將養殖所產生的污泥視為與工業及都市污水處理廠污泥為同一類需加以嚴格管理的廢棄物。依據行政院環保署 91 年 7 月針對「應先檢具水污染防治措施計畫之事業種類、範圍及規模」公告中，所謂「水產養殖業」之定義為：從事水產生物養殖之事業，漁牧綜合經營養殖面積在 0.5 公頃以上，一般淡水魚塭養殖面積在三公頃以上，鹹水魚塭養殖面積在六公頃以上者。環保署並訂出該水產養殖業的排放水須符合「放流水標準」：BOD5<30 mg/L、COD<100 mg/L及SS<30 mg/L，因此上述台灣漁塭廢排水顯然不符法規所訂的水質要求。雖然本國環保機關規定也頗為嚴格，但是至目前為止我國尚無實際行動控制養殖業造成的水污染問題。歸納之原因可能包括：

1. 水產養殖業的水污染防制工作(與工、礦廠事業廢水及市鎮家庭污水相比較)並不是現階段環保機關的稽查重點，因此對該事業的管制及稽查相當寬鬆；
2. 目前國內產、官、學界尚少有提出既有效率、又成本低廉可為漁民接受的水產養殖廢水處理方法，可適合推廣給多數養殖業所使用，因此沒有水產養殖業實際設置廢污水處理設施。

因此，若能開發出可行的水產養殖廢水處理及管理技術，提供目的事業主管機關及環保主管機關之參考及養殖業者使用，將有助於水產養殖業之合法管理及減輕其對環境造成的衝擊，使水產養殖業成為台灣永續發展的產業。

綜覽文獻，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、CO2、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。例如Zachritz and Jacquez [10]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 [11]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，各污染物的去除效率範圍分別介於：BOD5 37-67 %、SS 75-87%、氨氮 1-81%、亞硝酸氮 43-98%、硝酸氮 51-75%、TP 59-84%，皆獲得良好的處理效果。泰國Sananayuth [12]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分別可達：BOD5 91 %、SS 84%、TN 48%、TP 31%。德國Shulz. [13]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。

實驗方法

人工溼地系統之配置

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，改造完成本實驗之四個基本單元，即控制組養殖池（1138m^2）、循環水養殖池（1225m^2）、表面流動式人工溼地（FWS，free water surface flow，約 30 m^2）與表面下流動人工溼地（SSF，subsurface flow，約 75m^2）所組成。此人工溼地與循環水養殖池是以管線及抽水機建構成循環水養殖系統，循環池之養殖水以抽水機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養殖池是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，槽體深約 1.8 公尺，面積約 30m^2，由於水力停流時間及設計參數的關係，故設置溢流管將液位控制在 1.5 公尺， FWS溼地非種植蘆葦或香蒲，反種植浮水植物布袋蓮、水芙蓉，乃是讓懸浮固體物有較長時間的沉降，且亦利用其根系來吸收養殖過程中白蝦的排泄物及分泌物，和吸附水中之懸浮固體物，並分解或吸收飼料殘餘所產生的氮、磷。

而SSF溼地槽體面積約為 75m^2，槽深亦為 1.8m，其內鋪設 1.5m蚵殼後，於其上再鋪設約 0.15m碎石，因水力停流時間及設計參數的影響，故埋設一L型管，利用重力流方式將處理過後的養殖水放流回養殖池中，將液位約控制在 1.2m處，並於其上種植挺水植物如蘆葦、香蒲、莎草及美人蕉，種植密度約一平方公尺 4~5 株。循環水在此系統是經由碎石及蚵殼之孔隙而入滲至介質下層進行淨化來達到處理的效果。

人工溼地系統之操作

本研究進行了三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 95 年 1 月初至 95 年 5 月底，第三試程自 96 年 5 月至 96 年 7 月。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(每小時進流 15 分鐘)將循環池養殖水抽送至 FWS 濕地，再經由 SSF 溼地處理後出流。養殖期間，第一試程、第二試程及第三試程放養密度分別為每池 60,000、120,000 及 120,000 尾，每平方公尺分別約有 50、100 及 100 尾。

本研究中第一試程循環水平均流量為 463 CMD，循環水流經人工溼地的水力負荷平均為 4.41 m/d，水力停留時間平均為 4.57 hr。第二試程操作時循環水平均流量為 473 CMD，循環水流經人工溼地的水力負荷平均為 4.51 m/d，水力停留時間平均為 4.77 hr。第三試程操作時循環水平均流量為 306 CMD，循環水流經人工溼地的水力負荷平均為 2.92m/d，水力停留時間平均為 7.37hr，如表 1 所示。

採樣與分析

本研究試養殖期間，每週採集一次，如圖 1 所示有三個採樣點。採樣時，水樣以 1000mL之PVC瓶收集，於當時做DO、pH、溫度、導電度、濁度（Turbidity，NTU）及鹽度等現場監測項目，再攜回實驗室從事各項水質分析。水質分析包括以下：化學需氧量（Chemical Oxygen Demand，COD）、總懸浮固體（Total suspended solids，TSS）、氨氮（Ammonia Nitrogen，NH_4-N）、

亞硝酸氮（Nitrite，NO_2-N）、硝酸氮（Nitrate，NO3-N）、總凱氏氮（Total Kjeldahl Nitrogen，TKN）、磷酸鹽（Orth Phosphate，PO_4-P）、總磷（Total Phosphorus，TP）、總大腸菌類（total coliform）、葉綠素-a（Chlorophyll-a，Chl.a）、生化需氧量（Biochemical Oxygen Demand，BOD）等，依照環保署所列的方法（表 3.2）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, Germary）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。

結果與討論

本研究系統於 93 年 7 月操作至今，因中間遭逢颱風及水患之害，使本實驗區分為三個放養試程，其間對水質及白蝦生長及成本推估做分析統計，而白蝦生長僅以第三試程為例，做一分析探討。

水質的淨化

SS 的去除

試驗期間，循環水養殖池與經由濕地處理後出流水之SS平均水質濃度在第一試程中分別為 21±14 及 6±5mg/L；第二試程中為 23±12 及 8±5mg/L；第三試程中為 37±10 及 15±15mg/L。平均去除效率各試程分別為 78、54 及 59%（表 2）。先前研究[8,9]報導人工溼地處理室內高密度養蝦池的循環水，對SS的去除效率介於 55~69%，與本研究相當接近，甚至第一試程去除效率更達 78%。此結果顯示，人工溼地中對SS之良好的處理能力。由於溼地對SS的淨化，使得循環水養殖池的SS濃度經常低於控制組養殖池。在第一試程中控制組養殖池與循環水養殖池之SS平均濃度分別為 22±14 及 21±14 mg/L；第二試程中控制組養殖池與循環水養殖池之SS平均濃度分別為 62±45 及 23±12 mg/L；第三試程中控制組養殖池與循環水養殖池之SS平均濃度分別為 60±16 及 37±10mg/L；雖然在第一試程中控制組養殖池與循環池養殖池SS濃度水質分析差異不大，但仍有略低的情形。而在第二及第三試程中，循環水養殖池SS濃度水質分析顯著低於控制組養殖池（$p<0.05$），顯示人工濕地可有效地控制養殖池的SS水質。

葉綠素 a 之去除效率

葉綠素a可表示水中浮游性藻類細胞的指標，亦可做為養殖池內養殖密度之對照。試驗期間，而循環水養殖池與經由濕地處理後出流水之平均葉綠素a濃度在第一試程中分別為 34.9±31.1 及 14.1±13.1μg/L；第二試程中分別為 18.9±11.2 及 8.3±5.3μg/L；第三試程中分別為 37.6±24.1 及 9.4±5.6μg/L；平均去除效率各試程分別為 68、54 及 65%，三試程之間皆有顯著去除效率。另一項先前研究[7]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，在第一試程中控制組養殖池與循環水養殖池之平均葉綠素 a 濃度分別為 53.5±56.7 及 34.9±31.1μg/L；第二試程中控制組養殖池與循環水養殖池之平均葉綠素 a 濃度分別為 56.1±53.2 及 18.9±11.2μg/L；第三試程中控制組養殖池與循環水養殖池之平均葉綠素 a 濃度分別為 76.0±49.6 及 37.6±24.1μg/L；顯示人工濕地有效地控制養殖池的葉綠素 a 水質。

BOD 之去除

試驗期間，而循環水養殖池與經由濕地處理後出流水之BOD_5平均水質濃度在第一試程中分別為 5.6±1.6 及 2.9±0.75 mg/L；第二試程中分別為 6.2±3.0 及 3.1±1.7 mg/L；第三試程中分別

為 6.6±2.2 及 4.8±1.6 mg/L；平均去除效率各試程分別為 40、46 及 27%，第二試程處理效率略高於第一、第三試程。先前研究[8,9]報導人工溼地處理室內高密度養蝦池的循環水，對BOD_5的去除效率介於 37~54%，與本研究相當接近。此結果顯示，本研究儘管在第二試程中提高水力負荷操作，但是不影響人工濕地對BOD_5的去除效能，明顯看出人工溼地中SSF系統對BOD_5之良好的處理能力。

由於溼地對BOD_5的淨化，使得循環水養殖池的BOD_5濃度經常低於沒有循環水處理的控制組養殖池。表 2 顯示在第一試程中控制組養殖池與循環水養殖池之BOD_5平均濃度分別為 6.6±2.3 及 5.3±1.7mg/L；第二試程中控制組養殖池與循環水養殖池之BOD_5平均濃度分別為 10.5±2.6 及 6.2±3.0 mg/L；第三試程中控制組養殖池與循環水養殖池之BOD_5平均濃度分別為 10.1±2.6 及 6.6±2.2mg/L；循環水養殖池的水中BOD_5均顯著低於控制組養殖池（$p<0.05$）。顯示人工濕地有效地控制養殖池的BOD水質。

氮的去除

相對於先前的研究[8,9]，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%；而德國Shulz[11]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TN去除效率為 20.6~41.8%，受HRT顯著影響。故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。

另外，文獻[14,15]中提出白蝦(*Pacific white shrimp*)養殖，若池水總氨氮及亞硝酸氮若分別超過 2.44~3.95 mg TAN/L及 6.1~25.7 mg NO_2-N /L時，對蝦體即會造成顯著的毒性並增加致死率。然在本實驗中TAN及NO_2-N之濃度皆低於此限值，故蝦體並不會因此死亡。

磷的去除

由表 3 中控制組養殖池與循環水養殖池的總磷平均水質顯示，雖然在三試程中對總磷的去除效率並高，但仍可看出溼地處理出流水略低於循環水養殖池之池水。在第二及第三試程中亦可看出循環水養殖池比控制組養殖池濃度來的低。第一試程中可能因水力停留時間較短，故處理效果不明顯。

先前文獻[7]提出利用小型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TP去除效率分別介於 49~68.5%；美國Schwartz and Boyd[11]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：TP 59-84%。由上可知TP去除受HRT影響顯著。本實驗三試程的HRT分別為 4.57、4.77 及 7.37hr，皆在文獻範圍值內，故在未來可能會提高HRT來提升去除效率。

藻類的去除

養殖期間，白蝦除了以投入之飼料當食物外，其亦會將養殖池中的浮游性動植物當作其食物來源，如綠藻跟矽藻便是蝦子食物之一。在表 4 中可看出人工溼地出流水中的浮游性植物明顯少於循環水養殖池，除四角藻高於循環水養殖池外，但整體來看去除效率可達約 60%；進而從控制組養殖池與循環水養殖池比較，亦可看出循環水養殖池浮游性植物量略低於控制組養殖池，除了少數幾種浮游植物如屬矽藻類絲狀菱形藻、泉生菱形藻及穀皮菱形藻：綠藻類如及柵藻；裸藻類的囊裸藻及藍綠藻類的隱球藻，但整體來說循環水養殖池的總浮游植物細胞總數略低於控制池養殖池，故還是可見人工溼地系統對於浮游性生物的消減效率。

白蝦之生長

在飼養初期循環水養殖池白蝦的生長較控制組養殖池的緩慢，原因是傳統養殖第一個月基本上是不投入飼料，所以蝦苗食物來源便是水中浮游植物或動物，而實驗前面所提人工溼地對SS 葉綠素 a 有很高的去除效率，故可得知對白蝦而言，在循環水養殖池中的食物量會低於控制組養殖池，亦造成循環水養殖池的白蝦生長略低於控制組養殖池的。在有飼料的投入約 72 天後，循環水養殖池白蝦的生長已大於控制組養殖池。推估可能是因為控制組養殖池後期污染物濃度略高，因為本實驗控制組養殖池不像循環水養殖池之廢水有經過溼地處理過後循環再利用，所以可能導致池內污染越來越高，進而影響其生長速度。白蝦生長的體長、重量與養殖天數之關係如圖 2、3 所示。

結論與建議

1. 本研究中第一試程循環水平均流量為 463 m^3/d，循環水流經人工溼地的水力負荷平均為 4.41 m/d，水力停留時間平均為 4.57 hr。第二試程操作時循環水平均流量為 473 m^3/d，循環水流經人工溼地的水力負荷平均為 4.51 m/d，水力停留時間平均為 4.77 hr。第三試程操作時循環水平均流量為 306m^3/d，循環水流經人工溼地的水力負荷平均為 2.92m/d，水力停留時間平均為 7.37hr。
2. 人工濕地可有效的去除養殖循環水中的主要污染物包括：第一試程SS 78%、濁度 52％、葉綠素a 68 %、BOD_5 40%及COD32％；第二試程SS54%、濁度 54%、葉綠素a 54 %、BOD_5 46%及COD26％；第三試程SS 59%、濁度 65％、葉綠素a 65 %、BOD_5 27%及COD65％。由於人工濕地對污染物的處理效能使得循環水養殖池中SS、濁度、葉綠素a、BOD_5及COD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、TKN及TP並無顯著的去除效率，可能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。但是在第三試程中仍可看出循環水養殖池中的NH_4-N、NO_2-N、NO_3-N、TKN及TP仍有低於控制組養殖池的趨勢。
4. 系統需不定期採收，除可增加植物對營養鹽之吸收外，並可降低死亡之植物體，再度將營養鹽釋回水體中，而影響系統之去除效能。
5. 白蝦生長情況循環水養殖池初期體重及體長可能會略低於控制組養殖池，但飼養 100 天後可能因控制組污染物濃度漸增，導致控制組養殖池白蝦生長較循環水養殖池緩慢。

計畫成果自評

本研究計畫以現地建立實場規模的自然生態系統與魚塭連結，利用人工濕地系統作為養殖水及廢水的淨化單元，以利養殖池水水質維護及排廢水的處理，以實場之研究驗證溼地技術的實用性。本研究所建立之循環水養殖系統，已經陸續完成幾次的養殖並收成白蝦，目前仍持續操作中，期望在節省能源、節省水資源、節省養殖面積、節省設置成本及減輕養殖排廢水污染負荷等養殖條件下，獲致高品質的養殖水質條件，進而提高養殖物的存活率及單位面積養殖物收成率，以為永續水產養殖建立示範性的養殖農場。本研究計畫所建立之循環水養殖技術，已經可以實際應用於相關產業。

另外，經由本計劃的執行，在2005年投稿至第30屆廢水處理技術研討會，論文題目為：「人工溼地與魚塭結合成循環水養殖系統之可行性研究」，並協助一碩士班研究生完成碩士論文，題目為：「人工溼地與魚塭結合成循環水養殖系統之研究」，並且投稿至環工年會廢水研討會中，以口頭發表的方式發表論文。

在研究期間受到天候因素影響頗大，導致部分的研究試程並無法如期達到預期成果，例如養殖漁塭土堤的崩壞、流量計的故障，以及漁塭淹水導致蝦苗流失等問題，這些在研究期間所實際面臨的問題可做為未來技術推廣時之參考。

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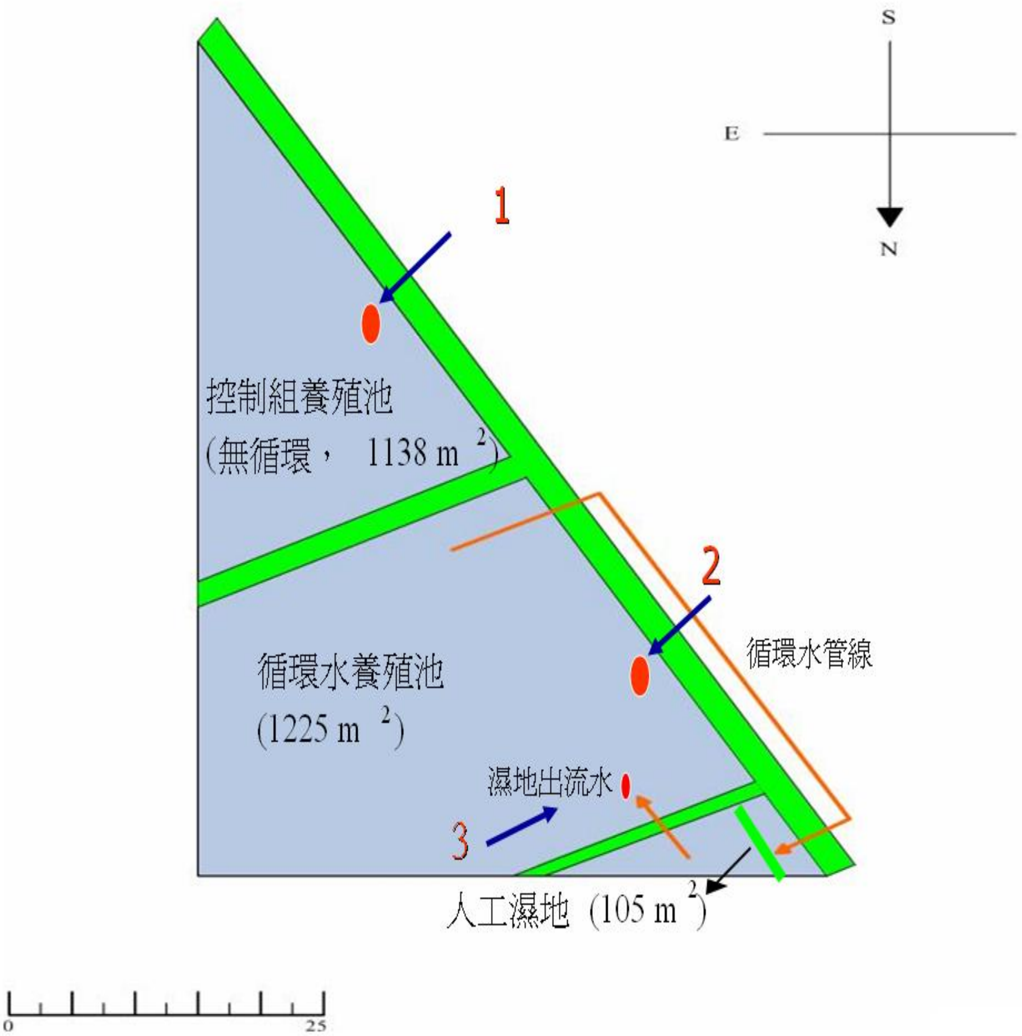

圖 1　「漁塭—人工溼地循環水示範系統」的配置圖與採樣點

表 1 三個試程各參數值

	平均流量（m^3/d）	每日循環比	平均水力負荷（m/d）	平均水力停留時間（hr）
第一試程	463	0.20	4.41	4.57
第二試程	473	0.21	4.51	4.77
第三試程	306	0.14	2.92	7.37

表 2 第一、二及第三試程三個試程主要污染物去除平均水質分析之比較

採樣點	SS（mg/L）	濁度（NTU）	葉綠素 a（μg/L）	BOD_5（mg/L）	COD（mg/L）
第一試程（*n*=11）					
控制組養殖池	22±14	19.0±7.8	53.5±56.7	6.1±2.1	53.5±25.8
循環水養殖池	21±14	15.0±5.1	34.9±31.1	5.6±1.6	42.8±13.5
人工濕地出流水	6±5	6.8±2.5	14.1±13.1	2.9±0.7	41.1±19.8
人工濕地處理效率(%)	78	52	68	40	32
第二試程（*n*=18）					
控制組養殖池	62±45	29.8±10.2	56.1±53.2	10.5±2.6	99.9±23.9
循環水養殖池	23±12	16.5±6.1	18.9±11.2	6.2±3.0	76.6±24.1
人工濕地出流水	8±5	6.6±3.2	8.3±5.3	3.1±1.7	67.4±16.3
人工濕地處理效率(%)	54	54	54	46	26
第三試程（*n*=10）					
控制組養殖池	60±16	34.6±13.5	76.0±49.6	10.1±2.6	76.0±49.6
循環水養殖池	37±10	18.3±12.4	37.6±24.1	6.6±2.2	37.6±24.1
人工濕地出流水	15±15	5.4±3.3	9.4±5.6	4.8±1.6	9.4±5.6
人工濕地處理效率(%)	59	65	65	27	65

表 3 人工溼地操作結果與養殖池水質分析

採樣點	TP（mg/L）	NO_2-N（mg/L）	NO_3-N（mg/L）	NH_4-N（mg/L）	TKN（mg/L）
第一試程（*n*=11）					
控制組養殖池	0.27±0.22	0.11±0.18	0.58±0.69	0.30±0.29	0.79±0.60
循環水養殖池	0.87±0.24	0.67±1.50	0.18±0.33	0.18±0.25	1.09±1.03
人工濕地出流水	0.86±0.26	0.32±0.31	0.23±0.43	0.42±0.52	0.98±1.00
第二試程（*n*=18）					
控制組養殖池	1.73±0.52	0.01±0.03	0.05±0.07	0.41±0.74	5.07±2.85
循環水養殖池	1.23±0.68	0.01±0.04	0.07±0.17	0.26±0.25	3.48±2.29
人工濕地出流水	1.05±0.60	0.01±0.02	0.89±3.46	0.42±0.42	4.82±2.81
第三試程（*n*=10）					
控制組養殖池	2.18±0.51	0.34±0.59	0.26±0.62	0.77±0.93	14.93±11.04
循環水養殖池	1.73±0.75	0.04±0.11	0.13±0.26	0.47±0.33	8.27±5.88
人工濕地出流水	1.45±0.81	0.05±0.08	0.09±0.07	0.60±0.46	10.57±8.23

表 4 各單元浮游植物細胞數

Taxa / Stations		控制組養殖池	循環水養殖池	人工溼地出流水
Bacillariophytes 矽藻				
Cyclotella meneghiniana	梅尼小環藻	116160	1452	0
Diploneis elliptica	橢圓雙壁藻	6996	6204	396
Navicula cryptocephala	隱頭舟形藻	2244	0	0
Navicula rhynchocephala	喙頭舟形藻	528	0	0
Navicula spicula	針舟形藻	396	0	0
Nitzschia filiformis	絲狀菱形藻	0	132	0
Nitzschia fonticola	泉生菱形藻	1320	12672	2244
Nitzschia palea	穀皮菱形藻	0	4488	1056
Chlorlphytes 綠藻				
Chlorella sp.	小球藻	3696	3168	2244
Crucigenia mucronata	十字藻	0	6336	0
Scenedesmus opoliensis	柵藻	6336	15840	4752
Scenedesmus sp.	柵藻	0	9504	0
Tetraedron sp.	四角藻	0	0	264
Euglenophytes 裸藻				
Trachelomonas sp.	囊裸藻	0	528	0
Cyanophytes 藍綠藻				
Anabaena sp.	魚腥藻	31680	25476	6204
Aphanocapsa sp.	隱球藻	0	101376	0
Chroococcus sp.	色球藻	3168	7920	1584
Merismopedia sp.	平裂藻	101376	76032	95040
Total(cells/l)		273900	271128	113784

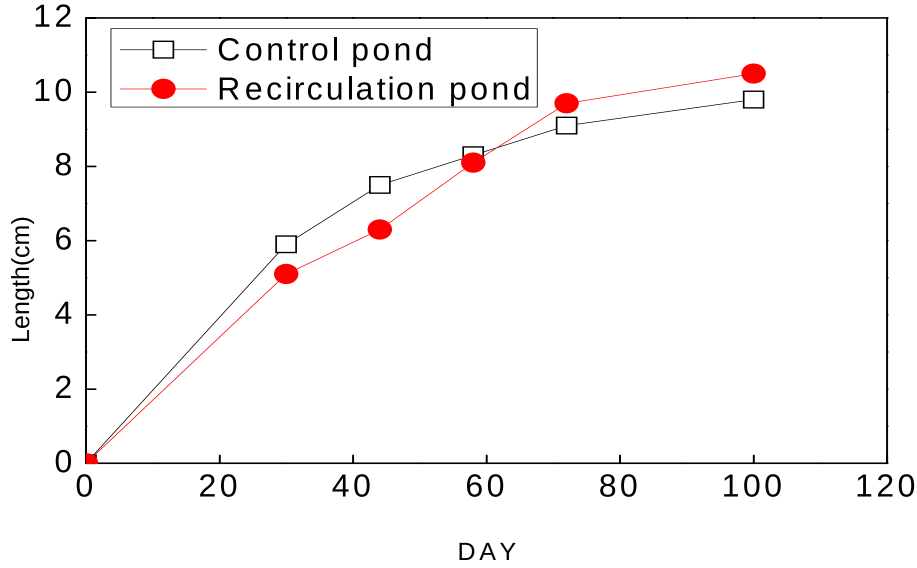

圖 2 第三試程白蝦飼養天數對體長之關係圖

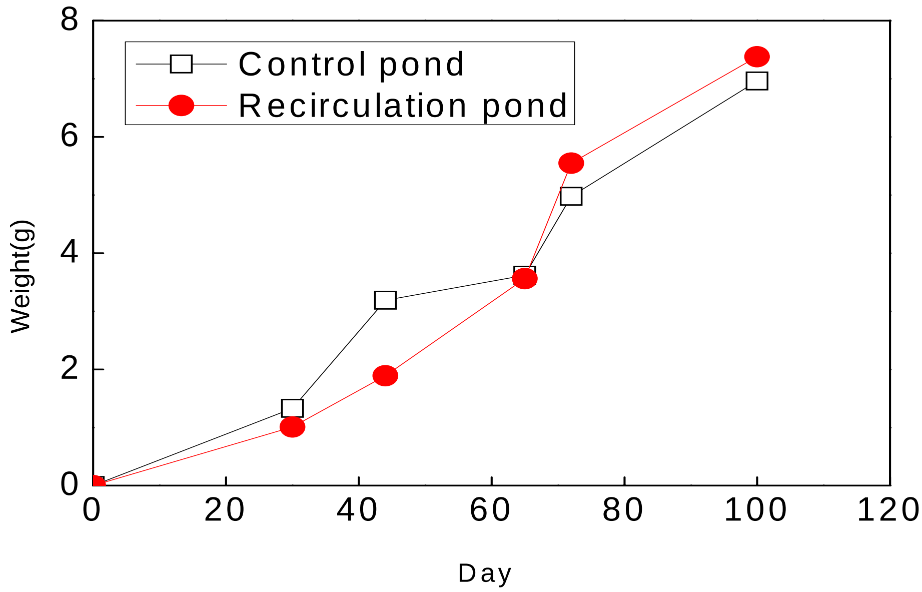

圖 4 第三試程白蝦飼養天數對重量之關係圖

可供推廣之研發成果資料表

□可申請專利 ■可技術移轉

※　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。

日期：年月日

國科會補助計畫	計畫名稱：**人工溼地技術永續管理水產養殖場水及廢水之研究**(II) 計畫主持人：林瑩峰 計畫編號：94-2211-E-041-023-　　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。

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

附件三

民國 95 年 10 月 26 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	2006 年 5 月 9~11 日 澳大利亞，墨爾本 (Melbourne, Australia)	本會核定補助文號	94-2211-E-041-023-
會議名稱	(中文) 2006 年環境學術會議暨環境工業展覽會 (英文) Enviro 06 Conference & Exhibition		
發表論文題目	(中文) Ecological Approaches for Decentralized Treatment and Reuse of Domestic Wastewater from Rural Communities (英文)鄉村地區生活污水處理與再利用的生態工法		

一、 參加會議經過

Enviro 06 Conference & Exhibition 是澳大利亞水協會(Australian Water Association)及廢棄物管理協會(Waste Management Association)，每兩年舉辦一次有關環境保護技術及管理策略的國際會議，並提供澳國環境保護及技術工業的展示及交流平台。自 2000 年起每兩年在澳國主要都市雪梨與墨爾本輪流舉辦，2006 年在墨爾本著名的國際會議中心舉辦，迄今已舉辦了四屆。整個會議分技術議程(Technical Program)及環保工業展示(Exhibition)兩類型同時進行，並以建構永續城市(Building Sustainable Cities)為此次大會主題。根據主辦單位統計與會者主要來自澳、紐及美國，亞洲人士則佔少數，來自政府機構、大學及研究機構、顧問公司等之專家學者總計約 6000 人與會。

在技術議程中又包含 23 個子題(streams)，並在國際間公開徵求論文及技術發表者。這 23 個子題分別為：

- 受污染土地及地下水的管理
- 永續都市發展的趨勢及方向
- 臭氣科學及管理的發展
- 土壤與地下水污染整治及管理
- 提升環境效能促進多重效益
- 履行永續城市的開發
- 社區與環境
- 永續建築
- 流域管理

- 廢水處理－2006 年發展中的水準
- 飲用水中的自然有機物
- 消毒－UV, 臭氧
- 都市地下水與水的硬體建設
- 環境監測及分析
- 水再利用
- 整合與去集中型的給水系統
- 有機物質回收的策略
- 都市產生零廢棄的規劃
- 都市固體廢棄物的處理

這些論文涉及題材廣泛，內容多偏向技術實務或政策管理，解決實際環保問題。國內前往與會的專家學者僅有本人。

另外，在環保技術工業的展覽場中有約 2~3 百家的國際環保企業參與，展示他們的技術及商品，涵蓋：環境品質監測、水與廢水處理、雨水處理及收集、固體廢棄物清除、空氣污染防治等環保設備及技術。

二、 論文發表

此次筆者有一篇論文的發表。為筆者與本校荊樹人教授、李得元副教授所合著的論文：「Ecological Approaches for Decentralized Treatment and Reuse of Domestic Wastewater from Rural Communities」，此篇論文被安排於「提升環境效能促進多重效益」屬於 associate paper。本人除了發表論文外，並參與了「水再利用」、「永續建築」、及「廢水處理」等子題的論文發表會。

三、 與會心得

整體而言澳洲是個水資源不豐富的國家，年平均降雨量不到 1000 mm，尤其近幾年全球氣候變遷，降雨量顯著減少乾旱情況嚴重，民眾普遍具有缺水的憂患意識，因此水再生利用(water recycling and reuse)的課題變成社會民生所關注與討論的議題，因而也帶動給水工業(water supply industry)的發展。水再利用的策略包含：

1. 再生水直接再利用於非飲用用途(reclaimed water for non potable uses)：所謂非飲用用途包括：土地及農地(如高爾夫球場、公園、停車場、校園、庭園、酪農畜牧場草皮、果園)澆灌、馬桶沖洗及洗衣機上，這些做法已能為大多數公民(>76%)所接受。
2. 非直接飲用水的再利用方式(indirect potable reuse)：將再生水與傳統水源混合。也就是將廢水或污水處理到飲用水標準，再與水庫中的水混合後已增加水源，再經一般給水工程的處理及輸送成為飲用水。此作法之社會疑慮較高，但是相對的也帶動水處理技術的發展。
3. 暴雨雨水的處理及回收再利用：收集降於街道或其他地區地面的雨水逕流，經過處理後使用於沖洗馬桶或花園澆灌。另外，經更高級處理以符合飲用水標準，而提供家庭使用。

台灣年降雨量豐富，水價低廉，民眾普遍缺乏缺水的憂患意識，並無建立水再利用的觀念，水再利用的市場及工業發展低迷。但是，隨著人口成長、水污染、氣候變遷，水資源逐漸短缺，而用水量逐漸增加，為世界各國必然的趨勢，台灣早晚必須步入澳國極盡辦法進行水資源再利用之途。

三、攜回資料名稱及內容

「Conference Proceeding in CD for the Enviro 06 Conference & Exhibition」。

Improving Environment Performance for Multiple Benefits

Thursday, 11 May 2006

Melbourne Exhibition and Convention Centre
MEC Meeting room 1

Jean Cannon EnviroAction

This stream is about assisting businesses to implement pro-active identification of environmental risks, risk analysis and building management systems. These systems then use the tools and techniques that are showcased in other streams. But to use these only is just reacting to and remediating problems rather than planning and preventing them. This stream will explore ISO 14001 - examples of industries demonstrating their environmental sustainability and managing their environmental risks.

Improving Environment Management By Implementing Greenhouse Friendly Systems

f3b

Sponsor *Chai* Jean Cannon EnviroAction

e6402	KEYNOTE - EMS in A Changing Climate: Benefits of Addressing Climate Change within Environmental Management Frameworks			
	10:30 - 11:00	David	Ugalde	Greenhouse Office
e6496	Industry Working With Government Everybody Benefits			
	11:00 - 11:20	Glen	Jones	Boating Industry Association of SA
e6404	Organisational Adaptation to Climate Change - A Commercial Perspective on Perceived Risks, Opportunities and Threats			
	11:20 - 11:40	Cecil	Camilleri	The Yalumba Wine Company
e6319	Lessons From the Australian Water Industry Roadmap for Future Urban Water Management			
	11:40 - 12:10	Nick	Apostolidis	GHD
e6225	Strategic Environmentally Preferred Procurement - Supply Chain Outcomes			
	12:10 - 12:30	Claudio	Senese	Maunsell Australia

How Industry is Using EMS as a Tool to Improve Environmental Outcomes

f3c

Sponsor *Chai* David Ugalde Greenhouse Office

e6339	KEYNOTE - ISO 14001 in the Auto Industry and Supply Chain-Challenges and Opportunities			
	14:00 - 14:30	Henry	Marszalek	Ford Motor Company
e6406	KEYNOTE - The Role of EMS for Better Environmental Outcomes in Victorian Agriculture			
	14:30 - 15:00	Olivia	Kemp	DPI Victoria

Bringing it All Together

f3d

Sponsor *Chai* Jean Cannon EnviroAction

e6407	Forum: Bringing it all Together			
	16:30 - 18:00	Jean	Cannon	EnviroAction

Improving Environment Management By Implementing Systems for Multiple Benefits; Associated Papers

f3x

Sponsor *Chai*

e6028	Ecological Approaches for Decentralized Treatment and Reuse of Domestic Wastewater from Rural Communities			
	-	Ying-Feng	Lin	Chia Nan University of Pharmacy

e6028

Ecological Approaches for Decentralized Treatment and Reuse of Domestic Wastewater from Rural Communities

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Shuh-Ren Jing; Department of Environmental Engineering and Science, Chia-Nan University of Pharmacy and Science, **jingsr@mail.chna.edu.tw**
Der-Yuan Lee; Department of Environmental Resources Management, Chia-Nan University of Pharmacy and Science, **leedy@mail.chna.edu.tw**
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EXECUTIVE SUMMARY

Due to the lack of sewage treatment system in Taiwan, domestic wastewater is untreated or improperly treated and has become one of the major polluting sources on natural water bodies. Interest in the development of decentralized treatment of wastewater has been increasing because it offers householders or small communities of reusing the reclaimed wastewater without expensive reticulated sewerage. The Government of Tainan County, in the southern Taiwan, has recognized a policy on pollution control of domestic wastewater, in that centralized treatment systems will be primarily provided in urban areas whereas decentralized treatment systems will be offered in rural communities. Ecological engineering methods, such as constructed wetlands, soil filtration system, and stabilization pond, have been examined as feasible decentralized treatment technologies, because they have common advantages of low cost, low maintenance, easy construction, and lack of need for heavy machinery and energy. Constructed wetlands can additionally provide wildlife habitats and enhance landscape aesthetics. To date, there have been three ecological engineering systems built to efficiently perform the wastewater treatment in Tainan County - Erhang constructed wetland system, Gangwei constructed weland system, and Dajia soil filtration system. The objectives of the study were to investigate the efficacy of the three ecological engineering systems for treatment and reuse of domestic wastewater from rural communities, and to evaluate their abilities to enhance the biological diversity. The results of influent-effluent water quality, monitored from July to December 2004, showed that all the three systems could effectively reduce the major pollutants from influent sewage, resulting in treated effluents that always satisfied the Discharge Standards. The treated wastewaters from the three systems were reused, rather than disposal, for irrigation of landscape, horticulture, or agriculture lands close to the treatment systems. The results of ecology survey demonstrate that ecological engineering treatment systems increased the diversity of flora and fauna in the landscape. Flora includes the macrophytes and ornamental plants artificially planted and the wild grasses or plants. Fauna includes a variety of birds, fish, amphibians, reptiles, insects, spiders, and aquatic invertebrates species. This study concludes that ecological engineering approaches are cost effective and technically suitable for on-site treatment and reuse of domestic wastewater from rural communities as well as enhancement of landscape and ecology aesthetics. Construction of more such systems in rural communities of Taiwan is being undertaken.

INTRODUCTION

Due to deficiency of appropriate sewerage system in Taiwan, domestic wastewater is untreated or improperly treated and has become one of the major polluting sources on natural water bodies. A large centralized treatment plant with reticulated sewer system is an efficient approach to solve water pollution problem; however, it requires high costs to install and maintain and long term for construction. With national funds becoming increasingly limited, most towns or cities cannot afford this type of conventional centralized approach. In Taiwan, only less than 15% of the population is currently connected to a centralized treatment plant. Moreover, wastewater treated by a centralized system is difficult to be reused because the distance between reuse location and treatment plant is normally too long (Ho, 1996). On the other hand, interest in the development of on-side (or decentralized) treatment of wastewater has been increasing because it offers householders or small communities of reusing the reclaimed wastewater without extensive infrastructure development and expenditure (Ho, 1996; Bakir, 2001).

A decentralized wastewater management system may include a number of on-site treatment sub-systems serving individual homes, clusters of homes, residential buildings, commercial or institutional establishments, in where wastewater is treated rather close to the point of origin and reuse (Wilderer and Schreff, 2000). A variety of technologies used for on-site wastewater treatment worldwide have been reported (Ho, 1996; Oron et al., 1999; Wilderer and Schreff, 2000). In Taiwan, there have been existing on-site treatment systems for residences. Old dwellings or clusters of homes normally use septic tank to separate feces solids from wastewater, but with failure in removing soluble pollutants. Since the past decade, new households or buildings have been regulated to adopt a "compact plant", including septic tank, biological contact aeration process, settling tank, and chlorination, which is similar to the technology of the centralized wastewater treatment plant. This plant is designed to not only retain feces or solids, but also remove organic mater and pathogens from wastewater. However, the knowledge and willing of householders or owners to operate such sophisticated facility is generally insufficient. Therefore, development in alternative on-site treatment technology with low cost, high efficiency, easy maintenance is essential for improving management of domestic wastewater, particularly from rural communities where cannot afford a centralized sewerage system.

Constructed wetlands, an ecological technology, have been successfully used for decades to treat various types of wastewater, including municipal wastewater, acid mine drainage, industrial wastewater, agricultural and urban storm runoff, and effluent from livestock operations (IWA, 2000). Comparing to conventional treatment system, constructed wetlands are characterized by the advantages of lower capital costs, lower dependence on energy and maintenance, because they are based on natural processes driven by solar energy and gravity. Moreover, the increased wetland ecosystem can provide landscape aesthetics and wildlife habitat. Treatment wetlands have been applied as on-site treatment technology for management of domestic wastewater from individual residences (Neralla et al., 2000), commercial or school buildings (House et al., 1999), or small communities (Luederitz et al., 2001; Greenway and Simpson, 1996).

In Tainan County, where is located in southern Taiwan, government has recognized a policy on pollution control of domestic wastewater, in that centralized treatment systems will be primarily provided in urban areas and decentralized systems will be offered in rural communities. Since 2001, the Bureau of Environmental Protection in Tainan County Government has initiated a series of projects to evaluate the feasibility of natural treatment systems, or so called ecological engineering methods, as on-side treatment technologies for decentralized wastewater management in rural communities. The technologies that have been examined include constructed wetlands, soil filtration system, stabilization pond etc. To date, there have been three ecological engineering systems built to efficiently perform the wastewater treatment - Erhang constructed wetland system, Gangwei constructed wetland system, and Dajia soil filtration system. The objectives of the study are to investigate the efficacy of the three ecological engineering systems for on-side treatment and reuse of domestic wastewater from rural communities, and to evaluate their abilities to enhance the biological diversity.

SITE DESCRIPTION AND METHODS

Erhang Constructed Wetland System

Erhang constructed wetland system (Figure 1(A)) was built at Erhang village in November 2001. It consisted of a stabilization pond, a free water surface (FWS) wetland, a subsurface flow (SSF) wetland arranged in series. The stabilization pond was measured by 36.2 m × 7.4 m (long and wide), and was divided into three equal-area sections along the long and flow direction. The first section was not planted with any macrophyte, whereas the second and third sections were planted with water lettuce (Pistia stratiotes) and water hyacinth (Eichhornia crassipes), respectively. Water depth of the pond was maintained at approximately 1.0 m. The FWS wetland was an S shape ditch with a dimension of 98.5 m long and 3 m wide. A 0.3 m thick local soil layer (Jender silty loam) lined the bottom, and the depth of the surface water was 0.5 m. The SSF wetland was 14.4 m long and 5.0 m wide, and filled with a 1.0 m thick layer of gravel (20 mm average in size), providing a void volume of 45%. The water depth of the gravel bed was controlled at 0.8 m by a discharge facility. Cattails (Typha orientalis Presl.) and common reed (Phragmites australis L.) were planted in the FWS wetland and common reed was planted in the SSF wetland. The total area of the treatment wetlands was thus estimated to be 635 m^2. Part of domestic wastewater from Erhang community, with the flow rate ranging from 30 to 90 m^3/day, was intercepted and pumped into the front part of the stabilization pond, and then flowed through the treatment wetlands by gravity.

Gangwei Constructed Wetland System

Gangwei constructed wetland system (Figure 1(B)) was built at Gangwei village in April 2004, and consisted of four FWS wetland cells, each measuring 21 m long × 10 m wide, and an ecological pond (2046 m^2) connected in series. Hygrophila pogonocalyx, Gymnocoronis sp., Ceratophyllum demersum, and cattails were planted in the FWS wetlands. Domestic wastewater collected from the community was pumped into the first FWS cell and then flowed through the wetlands by gravity.

(A)

(B) (C)

Figure 1 (A) Erhang constructed wetland system, (B) Gangwei constructed wetland system, and (C) Dajia soil filtration system for decentralized treatment and reuse of domestic wastewater from rural communities.

Dajia Soil Filtration System

This system was built in May 2004 and located at Dajia village. It mainly included an anaerobic digester (12.3 m × 9 m) and a soil filter (52.5 m × 15 m), which were established under the ground. The anaerobic digester was made of brick and concrete in main body, being covered with a gravel layer (50 cm thick) and then a soil layer (25 cm thick). The soil filter lined with impermeable plastic liners was divided into three equal-size compartments with connecting in parallel. Perforated distribution pipes were installed at the top of the inlet end of each compartment to conduct the flow of wastewater from the anaerobic digester to soil filter, while perforated collection pipes were installed at the bottom of the distal end of the compartment for drainage of the treated wastewater. The filtration medium filled in the filter comprised local soil (84%) and rice hull (16%). The land area above the ground of the treatment site was schemed as a garden planted with a variety of terrestrial and ornamental plants (Figure 1(C)). Part of domestic wastewater from Dajia community, with a flow rate ranging from 40 to 60 m^3/day, was collected and pumped into the anaerobic digester, and then passed through the filter via gravity flow. The treated wastewater was retained in an aboveground pond (3 m × 2 m) for reused.

Table 1 Performance of Erhang constructed wetland system in treating domestic wastewater from Erhang communities

Parameters	TSS	BOD_5	TN	TP	Total coliforms (CFU/mL)
Influent, mg/L	57	37	18.3	3.2	54,929
Effluent, mg/L	17	9	4.6	1.6	305
Removal efficiency, %	48	76	74	42	98
Removal rate, kg/day	1.67	1.39	0.68	0.07	
Areal removal rate, $g/m^2/d$	2.63	2.20	1.04	0.11	

Water Sampling and Analysis

Water samples were collected biweekly from the inlet and outlet of each treatment unit of the three ecological engineering systems. All water samples collected were stored in an ice container and transported immediately to laboratory for water quality analysis. Total suspended solids (TSS), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4-N), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), total phosphorous, and orthophosphate were determined for the samples in the laboratory, while temperature, dissolved oxygen (DO), and pH of the wastewater at each sampling location were also measured in situ when sampling was performed. All above measurement methods were according to Standard Methods (APHA et al., 1995).

Ecological Assessment

Ecological assessments included surveys of vegetation, bird, fish, amphibian, reptile, spider, insect, and benthic invertebrate. The species and the number of individuals for the species were observed and recorded. Ecological diversity was evaluated using the usual Shannon-Weiner index.

RESULTS AND CONCLUSIONS

Water quality improvement

The results of water quality monitored from July to December 2004 show that all the three systems could effectively reduce the major pollutants from influent wastewater, resulting in treated effluents that always satisfied the Discharge Standards, i.e. TSS < 30 mg/L, BOD5 < 30 mg/L, and total coliforms < 2000 CFU/mL (Tables 1~3). Erhang system reduced total suspended solids (TSS), 5-day biochemical oxygen demand (BOD_5), total nitrogen (TN), total phosphorous (TP), and total coliforms from influent sewage with efficiencies of 48, 76, 81, 42, and 98%, respectively (Table 1). In Gangwei system, TSS, BOD_5, TN, TP, and total coliforms in influent sewage were removed by 22, 60, 71, 67, and 70 %, respectively (Table 2). Removals of influent TSS, BOD_5, TN, TP, and total coliforms in Dajia system were 32, 74, 52, 45, and 94 %, respectively (Table 3).

Water Reuse for Irrigation

The treated wastewater from the Erhang constructed wetland system was conducted into a scenic pond and then was reused to irrigate the terrestrial vegetation in the wetland site and the coconut and horticultural plant on the farmland next to the wetland site. The farmlands of coconut and horticultural plant occupied approximately 0.3 and 0.2 ha, respectively. Effluent from the wetland was rarely discharged to the adjacent water bodies. Ditch irrigation was used to avoid the contact of treated wastewater with human. Coconut production was found to considerably increase after the treated wastewater being reused.

Table 2 Performance of Gangwei constructed wetland system in treating domestic wastewater from Gangwei communities

Parameters	TSS	BOD_5	TN	TP	Total coliforms (CFU/mL)
Influent, mg/L	58	14	4.9	3.7	1193
Effluent, mg/L	16	5	1.0	1.1	207
Removal efficiency, %	68	61	71	67	70
Removal rate, kg/day	5.12	1.08	0.32	0.32	
Areal removal rate, $g/m^2/d$	1.76	1.04	0.11	0.31	

Table 3 Performance of Dajia soil filtration system in treating domestic wastewater from Dajia communities

Parameters	TSS	BOD_5	TN	TP	Total coliforms (CFU/mL)
Influent, mg/L	24	40	27.9	3.3	261,599
Effluent, mg/L	19	7	13.4	1.9	18,742
Removal efficiency, %	15	74	52	45	94
Removal rate, kg/day	0.33	2.02	0.45	0.10	
Areal removal rate, $g/m^2/d$	0.21	1.31	0.29	0.07	

In Gangwei system, the treated wastewater was mainly recycled as the water supply of the large ecological pond for improvement of landscape aesthetic and ecology diversity. Irrigation of the terrestrial vegetation in the wetland site also used the treated wastewater. The treated wastewater from the Dajia system was recycled for irrigation of the ornamental plants in the garden above the soil filtration bed so as to create a site of recreation for residents of the community.

Ecological Assessment

The results of ecology survey demonstrate that the three ecological engineering treatment systems increased the diversity of flora and fauna in the landscape. Flora includes the macrophytes and ornamental plants artificially planted and the wild grasses or plants. Fauna includes a variety of birds, fish, amphibians, reptiles, insects, spiders, and aquatic invertebrates species. Dajia system was comparatively lower in ecological diversity probably because there was no sufficient wetland or pond to provide habitat for fauna, as indicating from a very low Shannon index for fish and reptile. Erhang system was likely with the highest ecological diversity among the three systems because this system had the longest duration of wetland operation.

In conclusion, ecological approaches, such as constructed wetlands, soil filtration system, stabilization pond, are cost effective and technically suitable for on-site treatment and reuse of domestic wastewater from rural communities. They can also provide multiple functions as enhancement of landscape and ecology aesthetics for the community. Construction of more such systems in rural communities of Taiwan is being undertaken.

Table 4 Shannon index of an individual type of fauna present in the three ecological engineering treatment systems

Type	Erhang system				Dajia system				Gangwei system			
	Aug	Sep	Oct	Nov	Aug	Sep	Oct	Nov	Aug	Sep	Oct	Nov
Bird	1.97	1.98	1.92	2.21	1.82	2.09	2.15	2.00	1.65	1.71	1.84	2.12
Fish	1.40	1.44	1.39	1.39	0.00	0.00	0.00	0.00	0.50	0.41	0.38	0.00
Amphibian	0.64	0.86	0.89	0.56	1.05	1.00	1.05	0.00	1.08	1.07	1.07	0.56
Reptile	1.42	1.22	1.54	1.47	0.00	0.00	0.00	0.00	0.68	0.67	0.95	0.67
Spider	1.27	1.98	2.26	2.30	0.43	0.41	0.58	0.64	0.90	1.48	1.60	1.54
Insect	3.09	3.28	3.33	3.02	2.68	2.73	3.11	2.92	2.30	1.88	2.26	2.25
Benthic invertebrate	1.18	0.95	1.07	1.18	-	-	-	-	1.90	1.96	1.85	1.93

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